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# Technology Overview: Circulating Fluidized-Bed Combustion

GCA Corp.
Bedford, MA

Prepared for

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Research Triangle Park, NC 27711

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# TECHNOLOGY OVERVIEW: CIRCULATING FLUIDIZED-BED COMBUSTION

Final Report

June 1982

Prepared by

Douglas R. Roeck

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16. ABSTRACT The report summarizes the current technical status of circulating fluidized-bed combustion (CFBC). Companies that are involved in investigating this technology and/or developing commercial systems are discussed, along with system descriptions and available cost information. CFBC is a second-generation FBC system that is well underway toward commercialization in the U.S. The CFB operates at higher fluidization velocity, lower mean bed particle size, and higher recirculation rate than conventional FBC. Probable advantages of CFBC over traditional FBC include: more flexibility in fuel selection, reduced number of fuel feed points, higher combustion efficiency, better calcium utilization, and lower NOx emissions. Potential process limitations that must still be evaluated, however, include equipment erosion due to the more severe operating conditions, separation of bed material from effluent gas, severity of cyclone separation equipment design, and power requirements for process and auxiliary equipment operation. Battelle Development, Lurgi, and Pyropower are the major companies involved in demonstrating the commercial viability of this process in the U.S. Lurgi and Pyropower are basing their CFB systems on technology already commercially demonstrated in Europe; after pilot-proving its process, Battelle is building the first commercial U.S. plant.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Pollution | Pollution Control | 13B |
| Combustion | Stationary Sources | 21B |
| Fluidized Bed Processing | Circulating Fluidized-bed Combustion | 13H |
| Fluidized Bed Processors | | 13I |
| Fluidizing | | 07A |
| Circulation | | 14G |

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## SECTION 1

## INTRODUCTION AND BACKGROUND

This report summarizes the current technical status of circulating fluidized-bed combustion (CFBC). Companies that are involved in investigating this technology and/or developing commercial systems are discussed in Section 2 along with system descriptions and available cost information.

The circulating fluid bed is described as being a second generation FBC in that the process attempts to remedy some of the potential limitations of conventional FBCs while still incorporating the inherent process advantages. The CFBC is also described as being in the transition region between a classical fluidized-bed and pneumatic transport (see Figure 1). At low gas velocities, a dense, bubbling classical fluidized-bed results having a well-defined bed surface. This mode of fluidization is characterized by low solids entrainment such that recycling is not always necessary. As gas velocities are increased, the bed surface becomes more and more dispersed and solids entrainment increases to the point that solids recirculation (usually with a cyclone) is required to maintain bed inventory. This state has been referred to as a "circulating" or "fast" fluidization. As shown in Figure 1, the mean solids velocity increases at a much lower rate than the gas velocity and thus in the circulating bed mode of operation, a maximum in slip velocity can be achieved with high heat and mass transfer rates. In conventional FBCs, superficial gas velocities are limited by bed entrainment velocities. Because heat release rates per unit base area are limited by the oxygen available for combustion, the bed entrainment velocity imposes an upper limit on the attainable heat release. Two techniques for increasing the heat release are pressurized operation or use of the fast fluidized-bed where fuel and sorbent are intentionally entrained. Heat release rates for circulating beds are roughly $2 \times 10^6$ Btu/ft$^2$-hr, compared to $0.8 \times 10^6$ Btu/ft$^2$-hr for conventional FBC units.

The major differences between the CFBC and the conventional FBC are that the CFBC is characterized by its high fluidizing velocity (>10 ft/sec), continuous recycling or recirculation of bed material, and either separate beds or zones for heat exchange. The fluidizing velocity generally ranges from 2 to 12 ft/sec for conventional FBCs while for the CFBC the range is about 10 to 30 ft/sec. At the same time, mean bed particle size is much smaller for the CFBC, 50 to 300 μm compared to 1000 to 1200 μm for the

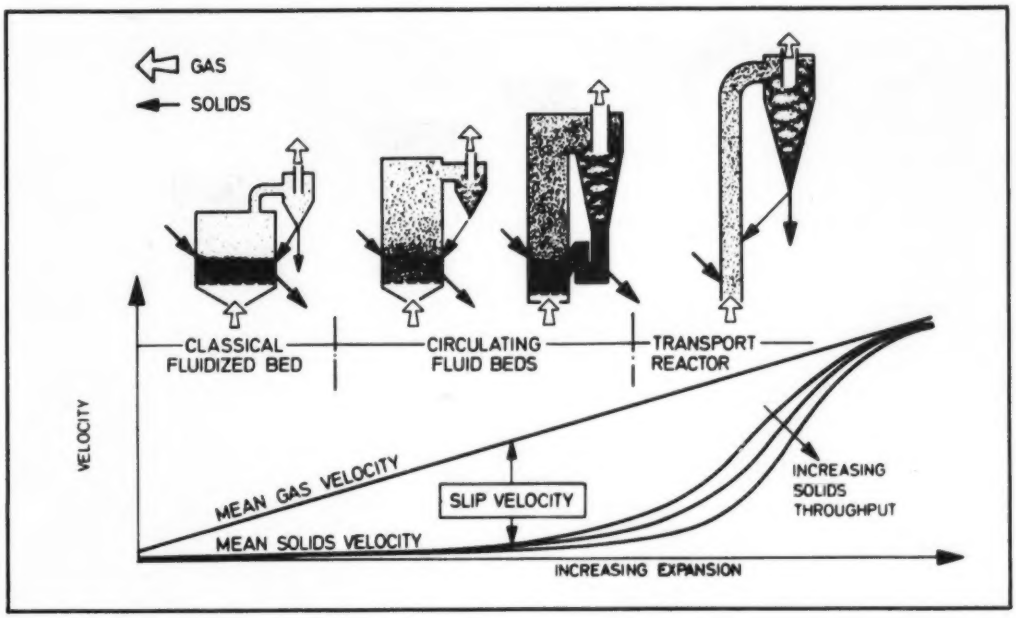


Figure 1. Basic fluid bed combustion systems.
Source: Reference 1.

conventional FBC. In the circulating bed mode of fluidization, the entire reactor contains solids of significantly lower density than in conventional fluidized-beds. In addition, the degree of gas-solids contact over the entire reactor height leads to longer contact times in the CFB, even at the high gas velocities employed.

Although dependent upon specific designs, advantages that have been reported for CFBCs over conventional systems include the following:

- the lower solids concentration (and hence density) and the increased turbulence resulting from the higher fluidizing velocity in the CFBC means that the number of feed points can be kept very low because of the excellent solids mixing.

- the CFBC offers more flexibility in terms of fuel choice (coal, wood, peat, etc.) than conventional FBCs.

- combustion air is supplied at lower pressures than required for conventional FBCs.

- the CFBC is capable of two to three times the fuel throughput per unit base area due to higher combustion air velocities.

- high turbulence and gas-solids mixing, strong solids backmixing, and continuous solids recirulation all help promote uniform combustor temperatures and high combustion efficiency (carbon utilization).

- the relatively fine coal and sorbent particle sizes used and long gas-solids contacting time combine to foster high utilization of limestone or dolomite sorbents such that calcium to sulfur (Ca/S) mole ratios of less than 2.25/1 are attainable while achieving greater than 90 percent $SO_2$ control.

- heat exchange surfaces need not be as critically designed or costly since they are usually separated from the combustion zone.

- staged combustion is possible to help minimize $NO_x$ emissions.

In addition to these apparent advantages, there are several potential problem areas (again dependent upon specific designs) as compared to classical FBCs:

- auxiliary power consumption may be increased because of feed material crushing and fluidizing blower requirements and overall system pressure drop.

- ancillary equipment requirements (hot cyclones, etc.) may be more significant in terms of number and severity of design.

- equipment erosion due to higher velocities is more of a concern.

- separation of bed material from effluent gas may be more difficult.

These reported advantages and disadvantages are more fully discussed in the next section as they relate to particular process configurations. Companies and organizations that are presently involved in circulating bed development and/or testing and which are discussed in the following section include the following:

Ahlstrom Company, Helsinki, Finland

Battelle Development Corp., Columbus, Ohio

Combustion Engineering, Inc., Windsor, Connecticut

Conoco Coal Development Co., Library, Pennsylvania

Electric Power Research Institute, Palo Alto, California

Gotaverken, Göteborg, Sweden

Lund Institute of Technology, Sweden

Lurgi Corp., River Edge, New Jersey and Frankfort, West Germany

Pyropower Corp., San Diego, California

Stone and Webster Corp., Boston, Massachusetts

Struthers Thermo-Flood Corp., Winfield, Kansas

Studsvik Energiteknik AB, Nykoping, Sweden

Tennessee Valley Authority, Chattanooga, Tennessee

Westinghouse R&D Center, Pittsburgh, Pennsylvania

## SECTION 2

## COMMERCIAL AND TECHNICAL STATUS

At the present time, the development and commercialization of circulating bed technology in the United States is being carried out primarily by the following groups:

Battelle/Struthers Thermo-Flood (joint venture)

Lurgi Corp./Combustion Engineering (joint venture)

Pyropower Corp.

In addition, Conoco, Stone and Webster, and Combustion Engineering are involved in a cooperative research program involving development of a slightly different system configuration. Each of these technical processes is discussed in this section based upon available literature and personal communications with each of the companies.

### BATTELLE DEVELOPMENT CORPORATION[2-8]

In 1973, Battelle began work on improving conventional coal-burning fluidized-bed combustion methods. As a result of these efforts, a new second-generation FBC process referred to as a Multisolid Fluidized-Bed Combustion (MS-FBC) system has been developed and patented.

As illustrated in Figure 2, the MS-FBC process features an entrained bed of small or light particles (typically sand or limestone) and a permanently fluidized dense bed (typically iron ore or silica)--both in the combustor. The light, entrained bed penetrates up through the dense bed and is elutriated from the combustor column. It is then collected in a cyclone and sent to an external heat exchanger. The cooled entrained bed material is then returned to the combustor. The entrained bed thus acts as the heat carrier in the process. The system is capable of burning either high sulfur coal or coke, or combinations of solid and liquid fuels.

Process features and perceived benefits of the MS-FBC system are indicated in Table 1. A comparison of a conventional FBC with the Battelle MS-FBC is provided in Table 2.

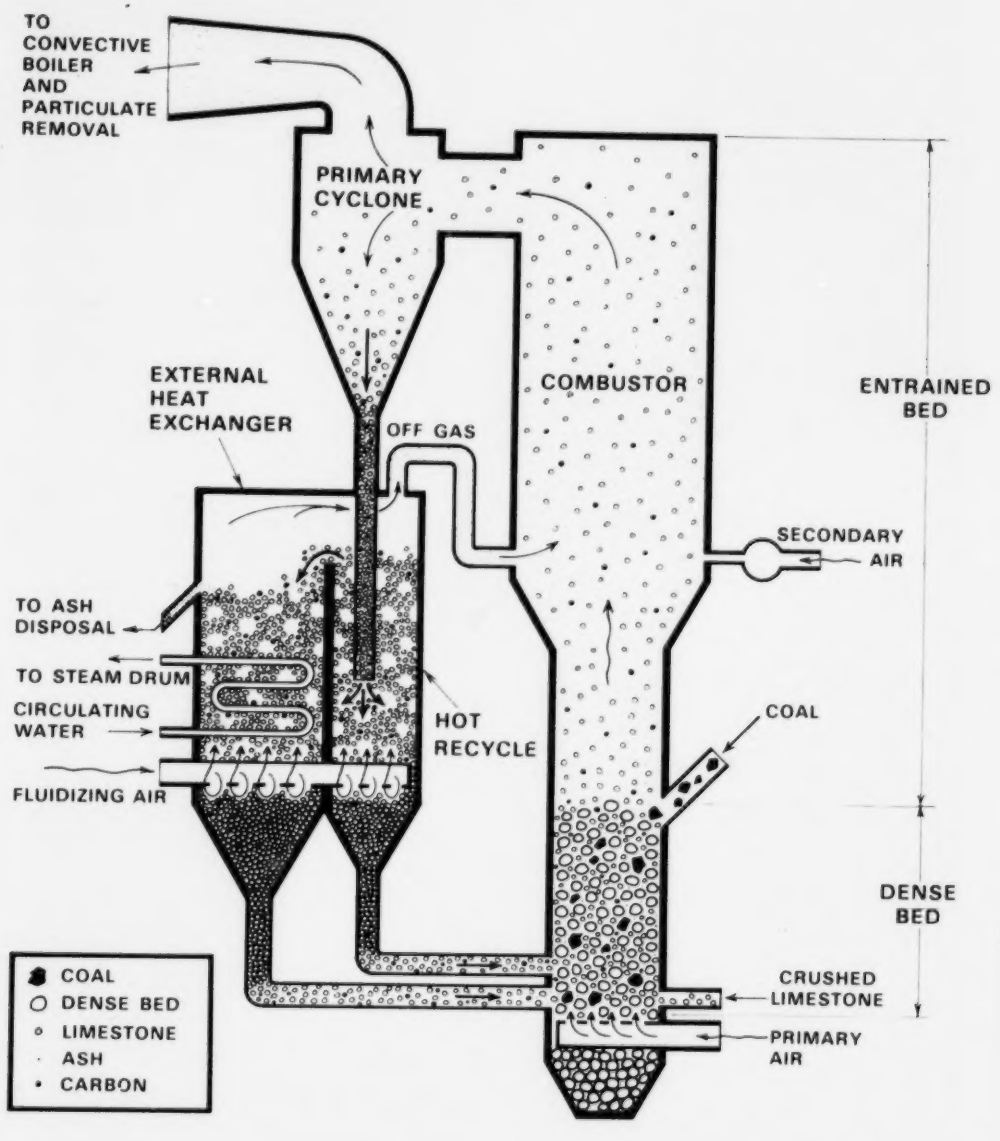


Figure 2. Battelle Multisolid Fluidized-Bed Combustor.
Source: Reference 8.

TABLE 1. FEATURES AND BENEFITS OF THE BATTELLE MS-FBC SYSTEM

| Features | Benefits |
|---|---|
| 1. Combustor and heat exchanger are decoupled. | Excellent response to load changes by changing entrained bed recirculation. Optimum combustor shape possible. |
| 2. Low fluidizing velocity (below 2 feet per second) with clean air in external heat exchanger/boiler. | May use horizontal heat exchanger tubes if desired, without concern over erosion of tubes. Extension of the life of the steam tubes and tube supports. Optimum heat-transfer coefficients. |
| 3. High fluidizing velocity (∿30 feet per second) in combustor amenable to staged combustion | Small cross section and violent mixing handles 1.5-inch-size wet lump coal. Staged combustion significantly reduces $NO_x$ emissions. No vulnerability to coal feed point location. |
| 4. Operates with crushed (minus 10 mesh) limestone. | Limestone structural stability is unimportant. Use of wider range of limestone possible. Lower consumption of limestone. |
| 5. Simple basic concept. | Flexibility in modifications and variations of design. |
| 6. Combustor has no heat-transfer tubes in dense bed. No cooling during startup or shutdown. | Maximum fuel flexibility without need for matching tube surface to fuel. Combustor will start up readily and remain hot during prolonged shutdown. |
| 7. Combustor freeboard has no cooling tubes, providing additional time at temperature. | Carbon burnup and limestone utilization are maximized. |
| 8. Addition of entrained bed in freeboard region of combustor. | Freeboard burning is controlled. |

Source: Reference - Report Summary: Battelle's Multisolid Fluidized-Bed Combustion Process.

TABLE 2. COMPARISON OF OPERATING CHARACTERISTICS OF CONVENTIONAL FBC AND MS-FBC.

| | FBC | MS-FBC |
|---|---|---|
| Superficial gas velocity | 12 ft/sec, max. | 20-30 ft/sec |
| Dense bed material | | |
| Type | Limestone or dolomite | Iron ore, etc. |
| Typical size | 8 x 30 mesh | 6 x 12 mesh |
| Particle density | 2.6 g/cc | 5.2 g/cc |
| Entrained bed material | | |
| Type | Not used | Sand |
| Typical size | - | 20-100 mesh |
| Particle density | - | 2.6 g/cc |
| Sulfur sorbent | | |
| Type | Limestone or dolomite | Limestone or dolomite |
| Typical size | 8 x 30 | Minus 10 mesh |
| Method of heat recovery | | |
| Steam tubes in dense bed | Yes | No |
| Steam tubes in freeboard | Yes | - |
| Steam tubes in entrained bed | - | Yes |
| Method of controlling dense bed Temperature | By immersed steam tubes | By adjusting recirculation rate of entrained bed solid |

Source: Reference 2.

Development work on the Battelle system has been conducted in 6-in. by 20-ft high (MSFB-0.4, capacity-0.4 x $10^6$ Btu/hr) and 10-in. by 27-ft high (MSFB-1, capacity-1.0 x $10^6$ Btu/hr) pilot plant units. The MSFB-0.4 (shown in Figure 3) has an enlarged freeboard diameter of 8-in. to provide greater residence time for gas-solids reactions. The configuration of the MSFB-1 pilot plant is similar to that of the MSFB-0.4 except that it has no enlarged freeboard area. Coarse fuel is fed to each unit by dropping it into the combustor above the dense bed while fine fuel and limestone are fed by pneumatic injection near the bottom of the dense bed. The flow of recycled solids is controlled by non-mechanical "L" valves.

A generalized integration of the advanced MS-FBC design into an industrial steam generation system is depicted in Figure 4. For a specific application, the integration and sequence of the various heat transfer steps would be optimized for the requirements of the particular plant. Steam superheating can be incorporated either in the flue gas circuit or external heat exchanger.

Feed systems inject solid fuel up to a nominal 1-1/2-in. size into the combustor at the top of the dense bed. For staged combustion, 25 to 40 percent of the total combustion air enters through the air distributor at the bottom of the combustor. The remaining air is added to the combustor in the freeboard section as secondary air.

Entrained bed material passing through the external boiler is cooled from 1500°-1700°F to 800°-1200°F (dependent upon the application) before being recycled to the combustor. The recycle stream flow rate is varied to control the combustor temperature at the desired level.

Thermal efficiency in the MS-FBC system is increased by heat recovery from the flue gas by a combination of one or more of the following heat-transfer operations: (1) steam superheater, (2) boiler section, and (3) feedwater heating. The flue gas is cooled from about 1600°F to approximately 400°F in the economizer zone before passing through final particulate removal equipment.

Testing in the Battelle pilot plant has been carried out on high-sulfur coal from Ohio, Illinois, and Pennsylvania. Limestones evaluated were from Piqua, Ohio and Grove, Virginia. Tan silica pebbles are used as the material in the dense fluidized bed while fine speculite, limestone, and a rounded sand were originally tried as the entrained fluidized-bed material. Sand is now used initially in the entrained bed and is gradually replaced by accumulated spent limestone.

Sulfur dioxide emission levels of 1.2 lb $SO_2/10^6$ Btu have been met consistently with Ca/S mole ratios of 1.5 to 2.2 while burning 4 percent sulfur coal. Figure 5 shows the effect of entrained bed recycle rate on sulfur reduction while Figures 6 and 7 show the effect of combustion temperature on sulfur retention and limestone requirement.

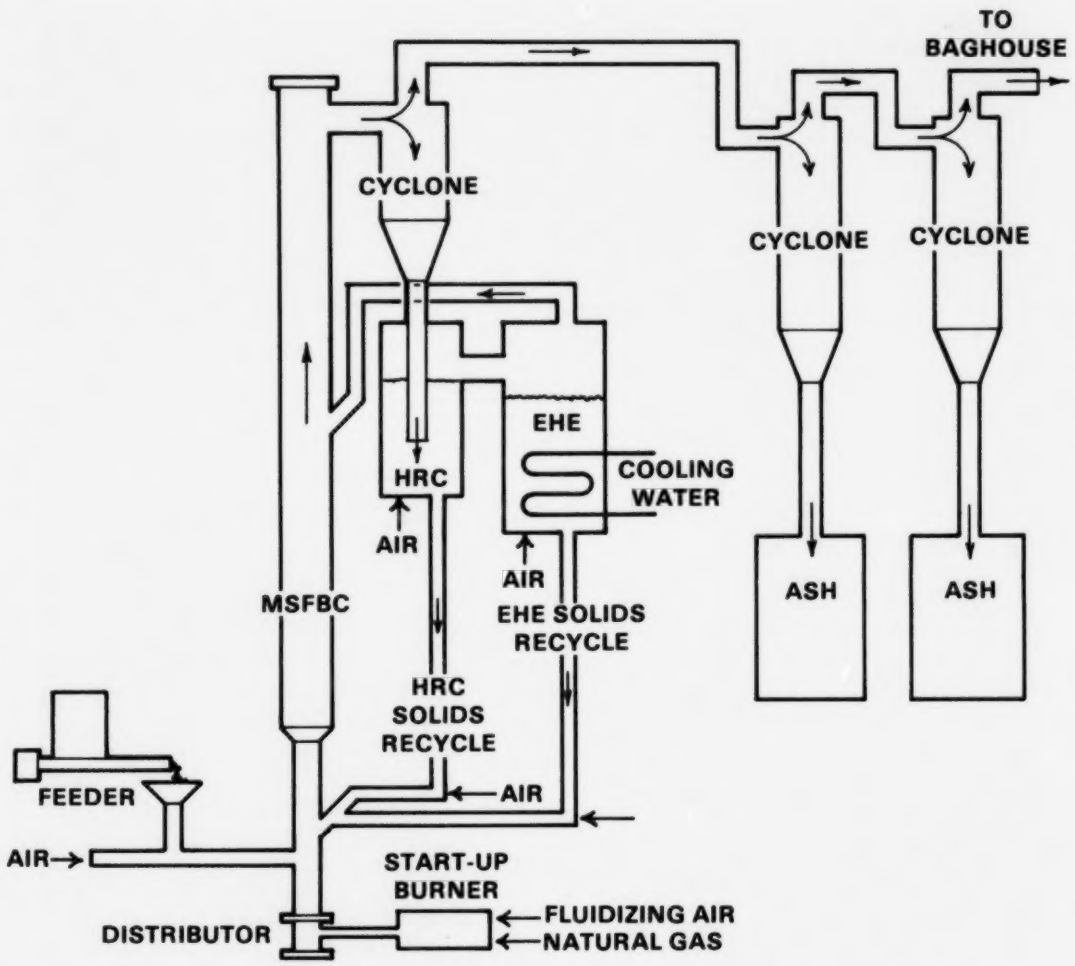


Figure 3. Schematic of MSFB-0.4 Pilot Plant.
Source: Battelle Memorial Institute.

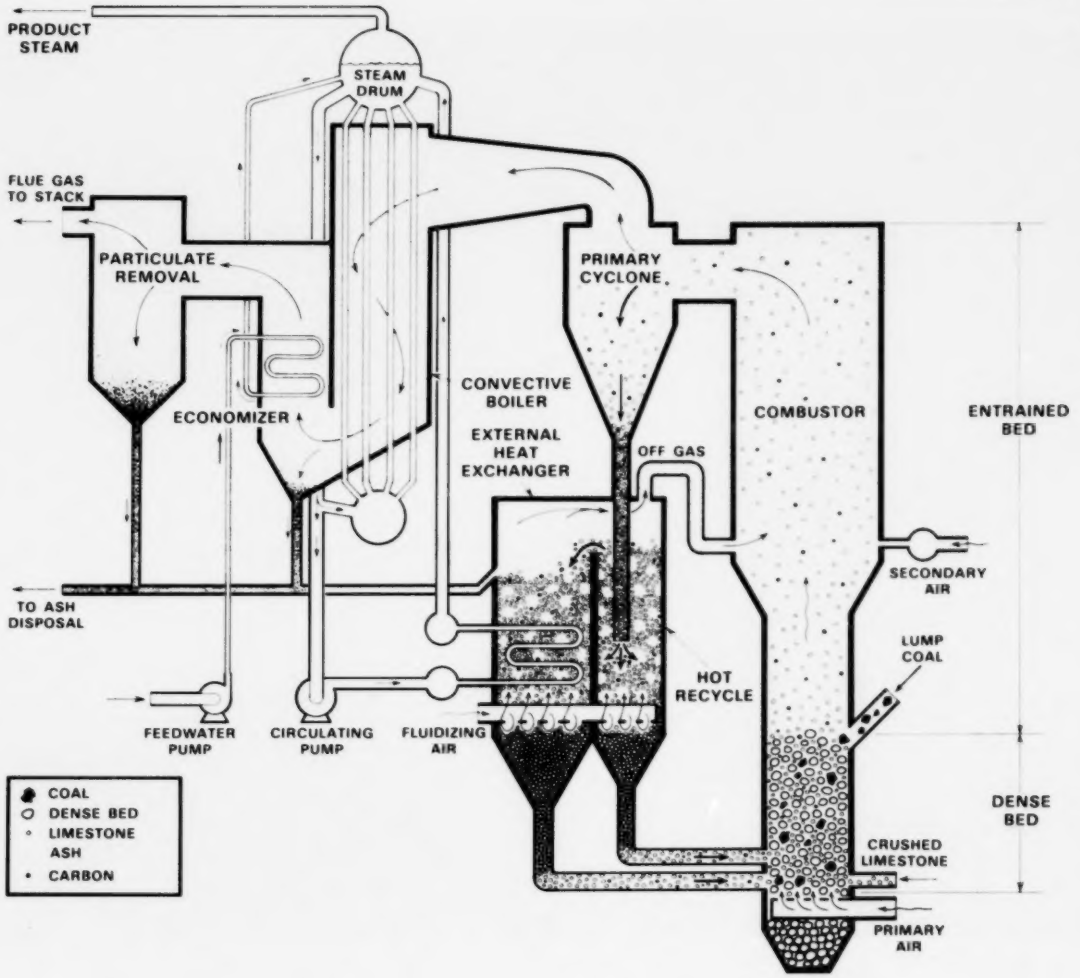


Figure 4. Battelle Multisolid Fluidized-Bed Steam Generator.

Source: Battelle Memorial Institute.

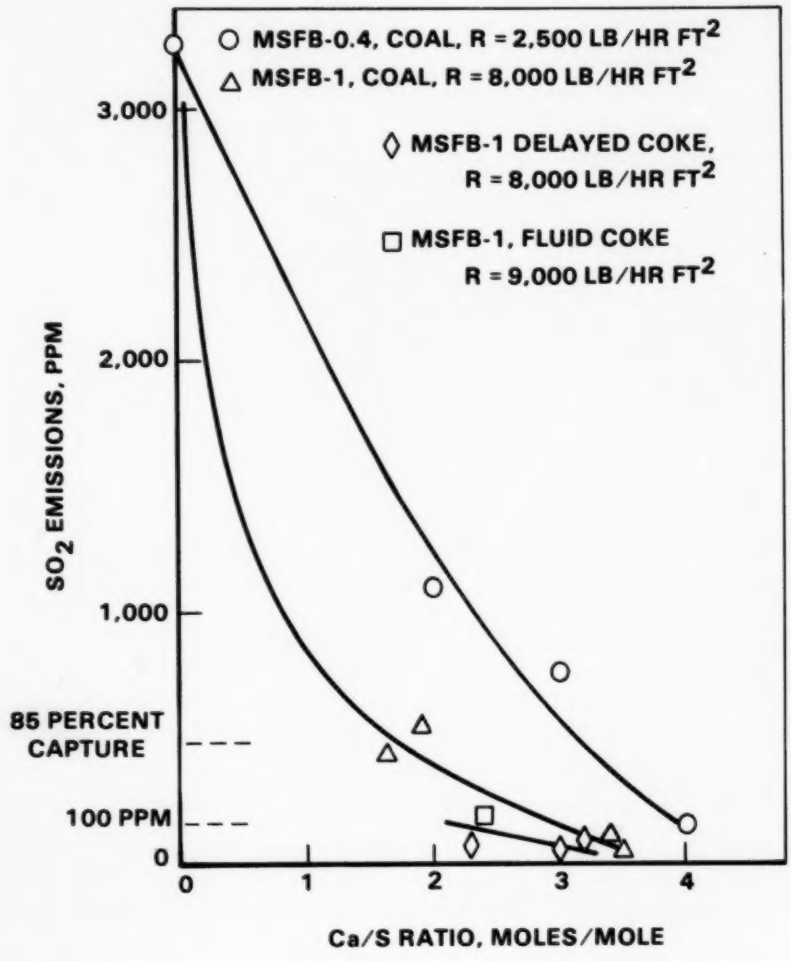


Figure 5. Sulfur Capture in MSBC - Effect of Entrained Bed Recycle Rate (R).

Source: Battelle Memorial Institute.

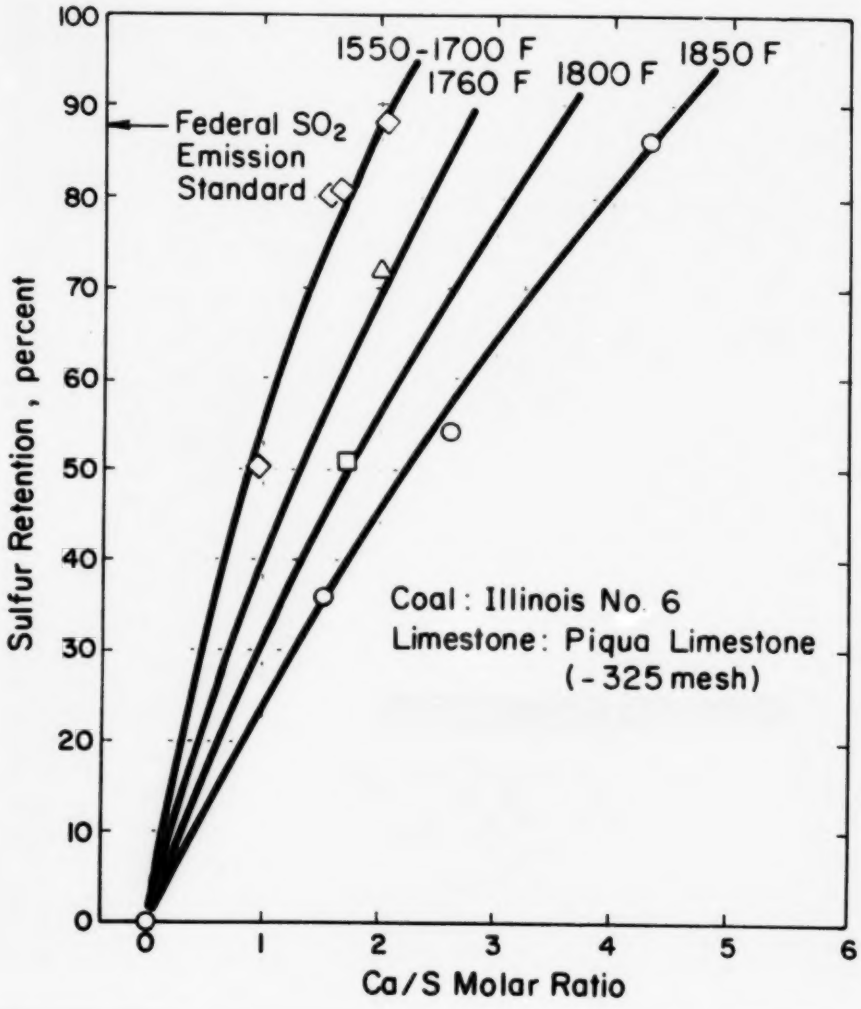


Figure 6. Effect of combustion temperature and calcium to sulfur ratio on sulfur retention in Battelle's MS-FBC system.

Source: Reference 2.

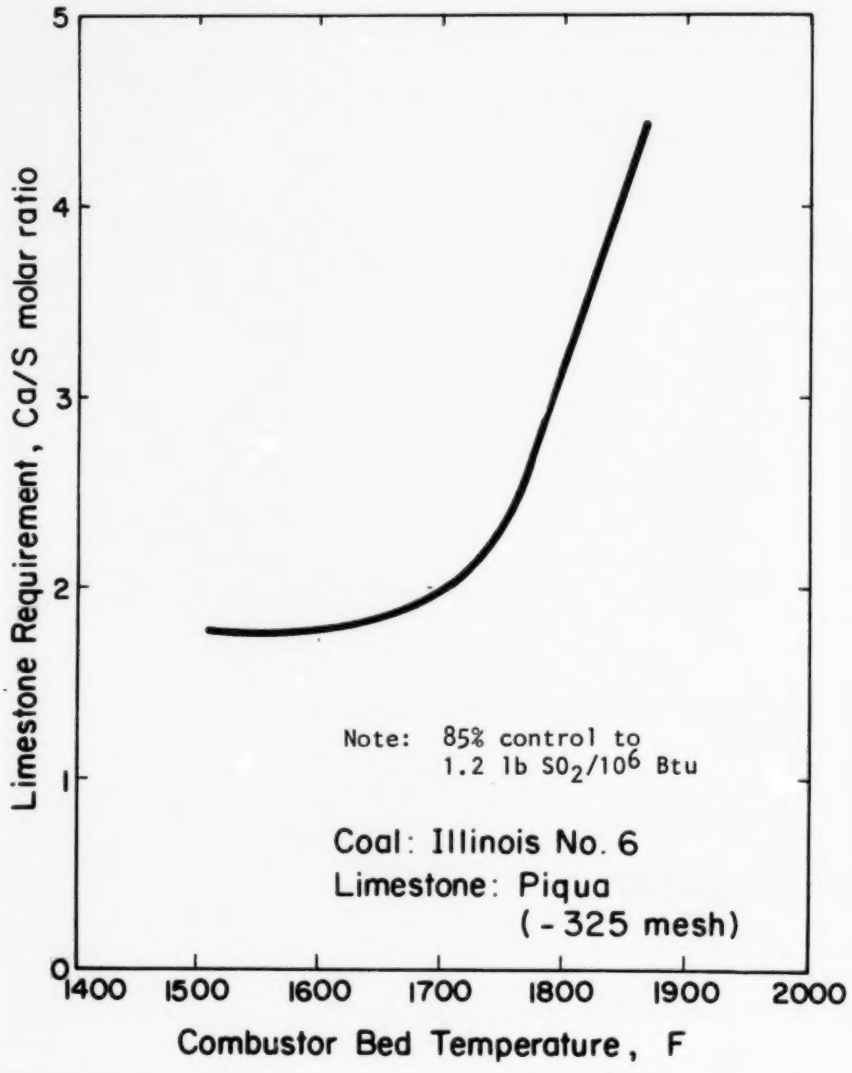


Figure 7. Effect of combustion temperature on limestone requirement in Battelle's MS-FBC system.

Source: Reference 2.

The commercialization of Battelle's MS-FBC has been initiated in conjunction with Struthers Thermo-Flood Corp. (a subsidiary of Struthers Wells Corp.) of Winfield, Kansas.[9-12] Struthers Thermo-Flood has concluded a license agreement with Battelle Development Corp. covering the MS-FBC system. The license gives Struthers Thermo-Flood exclusive worldwide rights to the design for use on secondary oil recovery steam generators.

Prior to the conclusion of the license agreement, Struthers Thermo-Flood had investigated several solid fuel-firing techniques including pulverized coal firing, traveling grates, slurry feeds, and fluidized-bed combustors. In its evaluations, Struthers judged each technique on the basis of the special design and operating characteristics required for its once-through oil field steam generators. Such factors as low and uniform heat fluxes, minimum heat retention, response to load changes, tube corrosion, tube fouling tendency, etc. were included in the overall evaluation program. Oil field steam injection projects impose significantly different requirements on steam generators than conventional steam generation applications; in most cases, the requirements are even more severe than supercritical electric utility boilers. Well-designed oil field steam generators must meet the following minimum criteria:[9]

- Operate satisfactorily with zero hardness feedwater at temperatures of 60°F to 220°F containing up to 12,000 ppm total dissolved solids.
- Be capable of responding to rapid and significant changes in load demand as dictated by injection well requirements with turndown ratios of greater than 4/1.
- Operate at high thermal efficiencies (88 to 92 percent based upon the lower heating value of the fuel).
- Operate in a largely unattended mode while providing high operating reliability coupled with a design incorporating ease in maintenance.

As a result of the evaluation program, Struthers chose the fluidized-bed combustion system as the solid fuel-firing technique most suitable for oil field steam generators, specifically the Battelle MS-FBC system.

At present there are two MS-FBC units being installed in the United States. The first is a $5 \times 10^6$ Btu/hr pilot plant unit with complete material handling, steam generation, flue gas processing, and control systems capability being installed at the Struthers Thermo-Flood facility in Winfield, Kansas. This pilot facility will be utilized for evaluation of enhanced oil recovery and process heater applications as well as further fuel testing and development of system improvements.

A second MS-FBC unit rated at $50 \times 10^6$ Btu/hr is installed and undergoing startup at a Conoco facility in Uvalde, Texas. This steam generator is designed to burn a wide variety of solid fuels including petroleum coke, coal, and lignite for steam injection being utilized in a tar sand reservoir. Steam, at an outlet pressure of 2450 psia, will be produced

from feedwater ranging in temperature from 70° to 220°F. A schematic diagram of the Battelle/Struthers oil field steam production configuration is shown in Figure 8.

## LURGI CORPORATION[1,13-17]

Lurgi, an engineering company serving the chemical and metallurgical industries, has over 30 years experience in the design and construction of high temperature fluidized-bed processes and hardware. In particular, 230 roasters for pyrite or zinc sulfide, 60 sludge incinerators and 60 pickle acid regeneration units were built using conventional bubbling bed technology.

In order to process fine grained materials at large gas velocities, Lurgi began developing circulating fluid bed technology around 1960. Their initial application was for calcination of aluminum trihydrate to cell-grade alumina, the Lurgi-VAW process, with the first commercial plant going on-line in 1970.

In this type of application, temperature uniformity throughout the reactor is most important to assure uniform alumina properties. A temperature deviation in any part of the furnace and cyclone of less than 20°F from a preset temperature can be achieved at operating temperatures of up to 2650°F with the large internal and external solids recirculation rate. Heavy fuel oil or natural gas is burned in two stages with preheated fluidizing air at a total excess air level of 10 percent and less (see Figure 9).

Fuel and primary air are injected into the lower part of the furnace, resulting in partially gasifying combustion. Secondary air is introduced through tuyeres in the upper part of the furnace, providing complete combustion under low excess oxygen. A typical flow scheme of the process is shown in Figure 10.

Combustion temperature is controlled by regulating the addition of aluminum trihydrate and in spite of temperatures as high as 2650°F, $NO_x$ emissions of 40 ppm have been achieved with natural gas firing. Solids retention time in the circulating fluid bed calciner is controlled automatically by varying the discharge rate and can be adjusted in wide limits with bed pressure drops between 28 to 80 in. W.C.* Other applications of the circulating fluid bed for high temperature, endothermic reactions, such as calcination of dolomite and limestone and decomposition of sulfates and hydrated aluminum chloride are in the realization or scale-up phase.

Based on this experience with roasting and combustion in conventional fluidized-beds and with the operation of circulating fluid bed alumina calciners, Lurgi began developing CFBC technology as an alternative approach to coal combustion. This work led to several novel process design concepts.[13-15] One possible design concept is illustrated in Figure 11 showing the flow scheme for a CFBC boiler plant. Fine-sized solids are fluidized at velocities of 20 to 26 ft/sec. Fine-grained coal (average

*W.C. - Water Column.

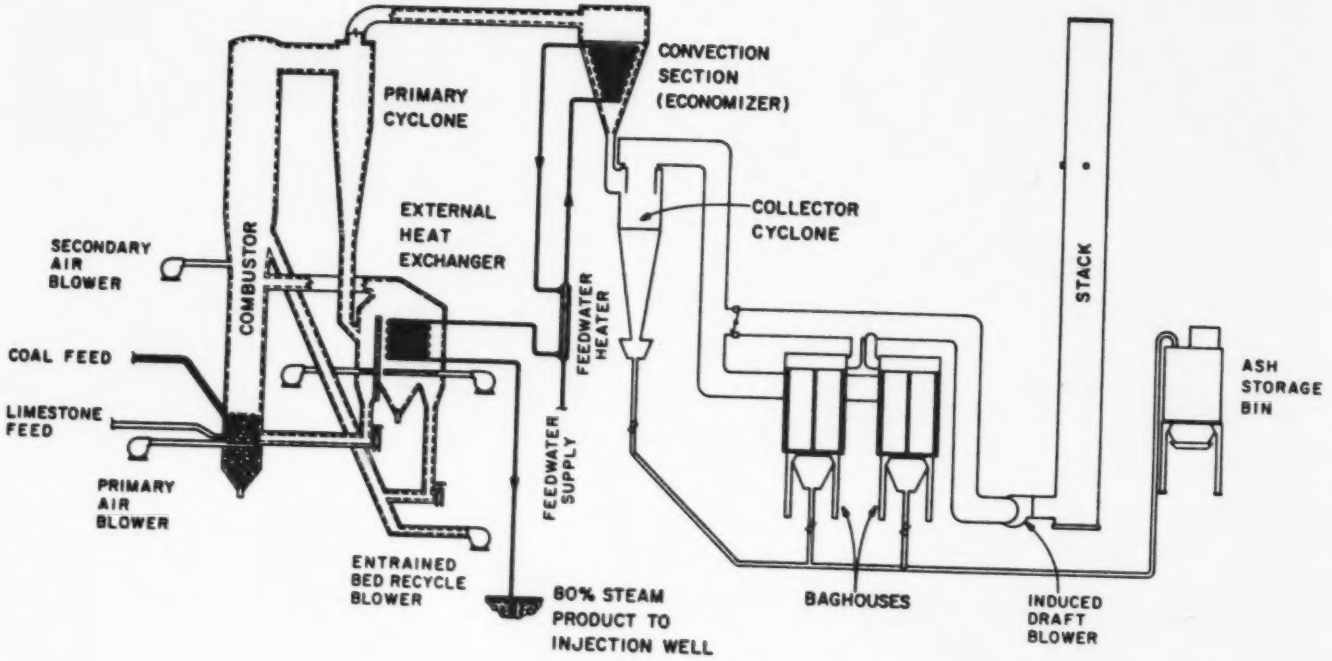


Figure 8. MS-FBC for oil field steam injection.
Source: Battelle Memorial Institute.

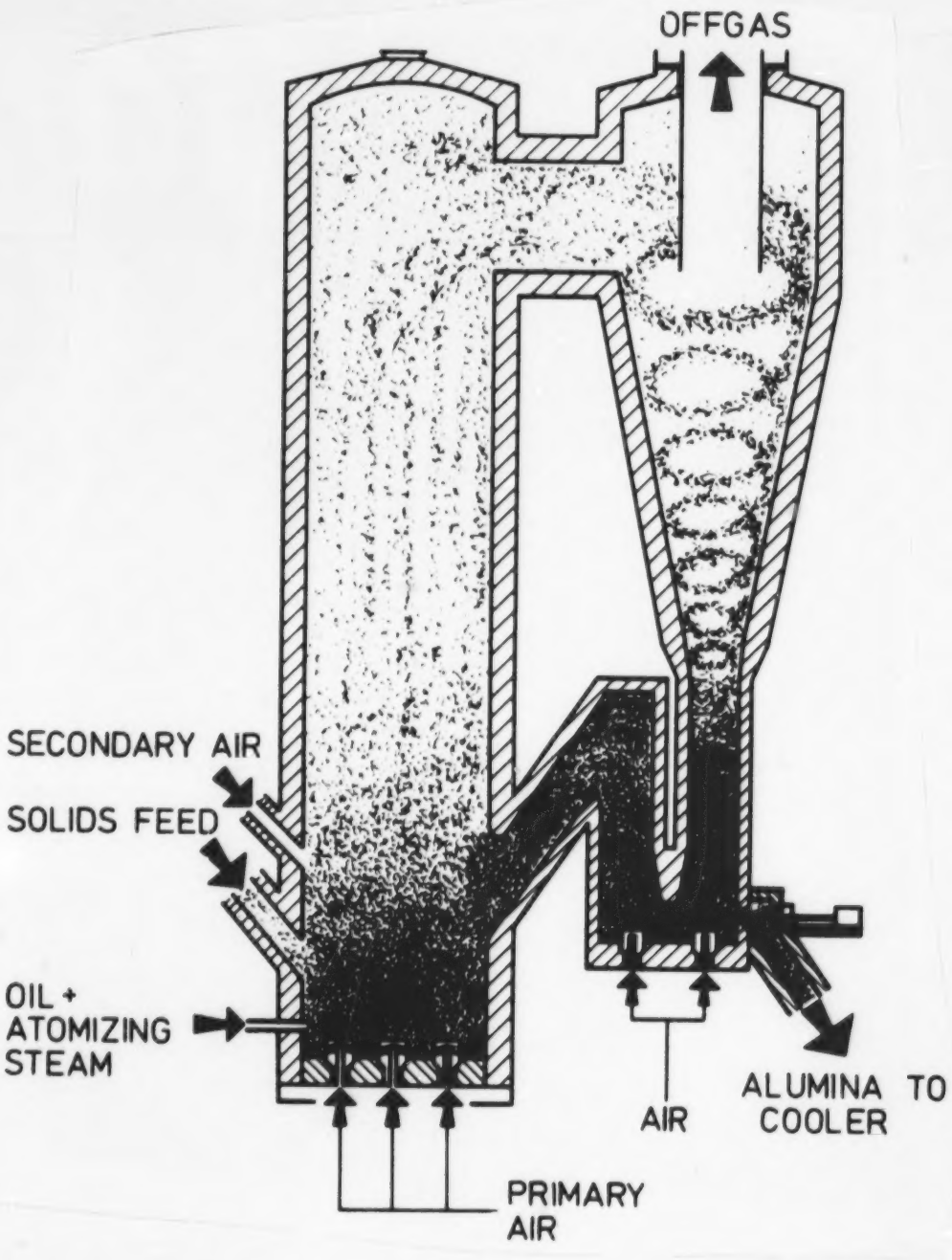


Figure 9. Two stage combustion in a circulating bed.

Source: Reference 1.

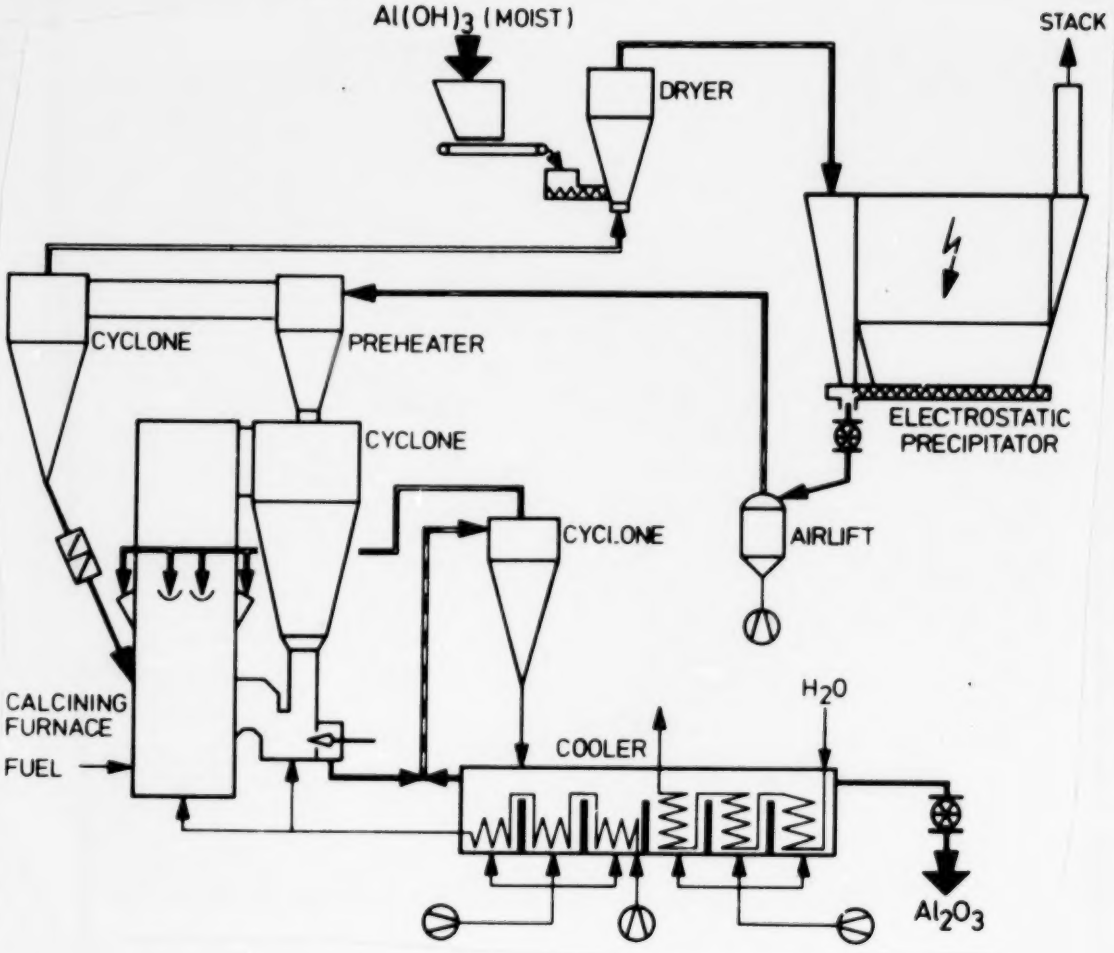


Figure 10. Flow diagram of a circulating fluid bed alumina calcining plant.

Source: Reference 1.

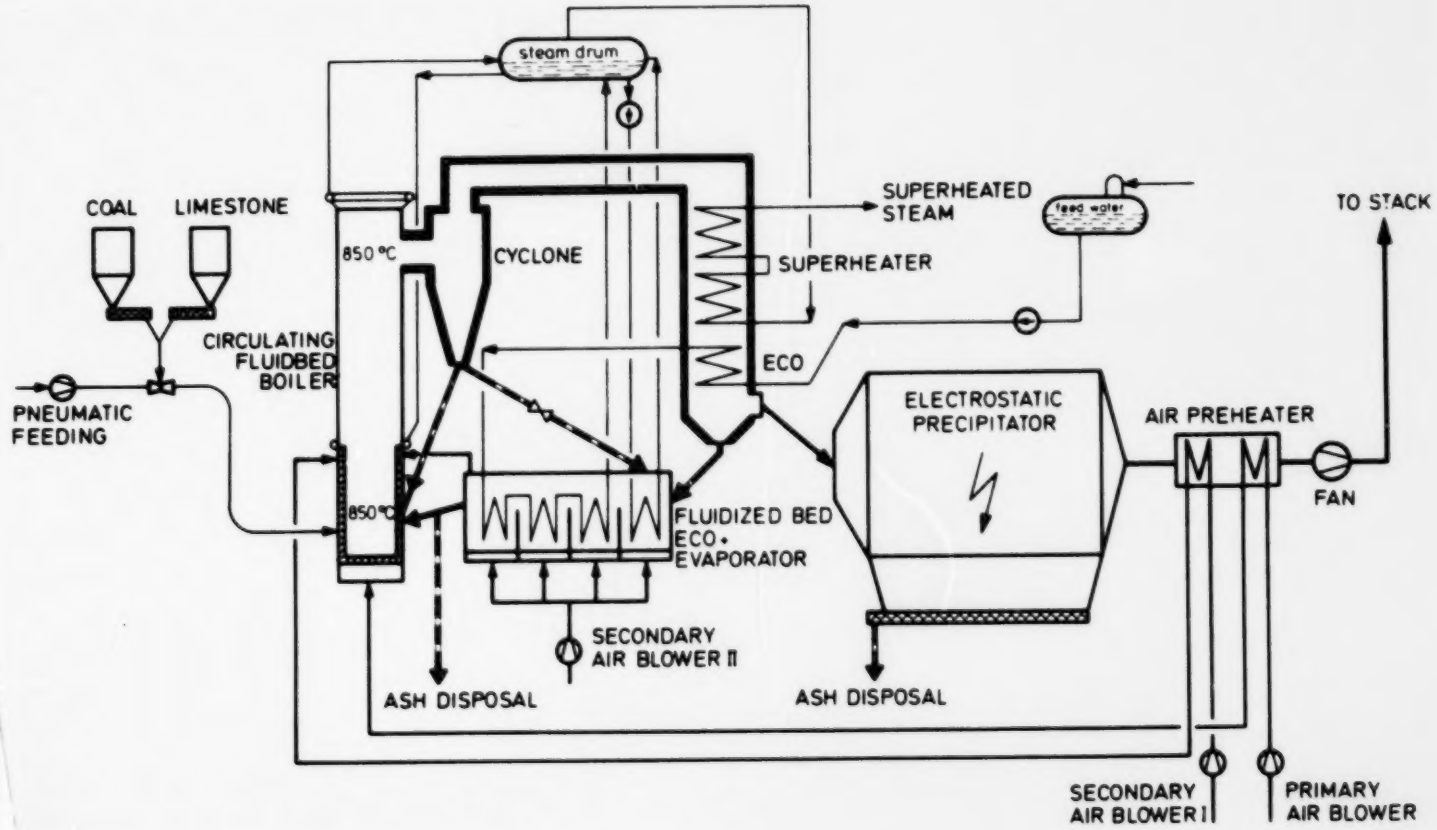


Figure 11. Circulating fluid bed boiler scheme.

Source: Reference 1.

particle size of 200 to 300 μm) is pneumatically fed to the lower part of the reactor. The number of feed points can be kept low because of the excellent solids mixing in the low density bed. Lurgi envisions two coal feed points for a 100 MW(e) boiler. Combustion air is introduced at two levels as shown in the diagram with combustion able to be sustained at constant conditions with bed temperatures of 1470° to 1830°F at 10 percent excess air.

In the combustion of high sulfur coal, limestone of roughly the same size as the coal is added to the bed for $SO_2$ removal. $SO_2$ removal efficiencies are enhanced by long gas-solids contacting times due to the presence of bed material throughout the height of the reactor, usually 50 to 100 ft high.

For the flow scheme shown in Figure 11, the combustion chamber is refractory-lined in the lower section for protection from the reducing atmosphere and to facilitate startup. Above the zone of secondary air injection, the bed is bounded by evaporator tube walls. Heat transfer from the bed to the tube walls depends on bed density and varies from 20 to 40 $Btu/ft^2$-hr-°F for the proposed operating conditions. While most of the solids collected in the cyclone are returned to the reactor by a fluidized syphon, a controlled portion flows through a fluidized-bed heat exchanger where high temperature solids are cooled by heat exchange with immersed superheater, evaporator or economizer surfaces. In the particular flow scheme shown, the tube bundles are forced convection evaporator surfaces in the entrance section and economizer surfaces in the exit section, although other configurations are possible. The heat transfer in this heat exchanger is high because the fluidizing velocity can be adjusted to optimal conditions without affecting combustion air requirements as in classical FBCs.

Combustion tests have been performed in the CFBC unit at the Lurgi Research Laboratories in Frankfort, West Germany. Two subbituminous coals and one limestone were tested. Coal properties, parameters varied, and results are shown in Table 3. These data show the excellent carbon combustion efficiency and high removals of nitrogen oxides and sulfur dioxide obtained during the test program. Further development, evaluation and testing in the Lurgi pilot plant have led to claims that the process is capable of achieving 90+ percent $SO_2$ reduction and 99.5 percent combustion efficiency at a Ca/S molar ratio of 1.2.

The excellent test results, design studies, and experience with circulating fluid bed calciners and the published results of combustion in classical fluidized beds have led Lurgi to develop the tentative comparison between their CFBC design and conventional FBCs shown in Table 4.

The CFBC process and hardware technology are similar to the Lurgi-designed alumina trihydrate calcining process of which there are 24 such units installed or under construction worldwide.* Lurgi Corp. is presently in the process of commercializing circulating fluidized-bed combustion technology in the United States although there are currently no such units installed. In

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*Personal Communication between Doug Roeck, GCA, and Phil Mantin, Lurgi Corp., August 5, 1981.

TABLE 3. TEST PARAMETERS FOR COAL COMBUSTION IN THE LURGI CIRCULATING FLUID BED COMBUSTION FACILITY

| Coal types | "A" | "B" |
|---|---|---|
| Volatiles, % | 20.8 | 21.2 |
| Ash,[a] % | 40.8 | 20.7 |
| Sulfur,[a] % | 1.31 | 1.23 |
| Nitrogen,[a] % | 1.02 | 1.50 |
| Low heating value, Btu/lb | 8,100 | 12,000 |
| Mean particle diameter (feed), μm | 237 | 300 |
| Max. coal feed rate, lb/hr | 50 to 60 | |
| Combustion temperature, °F | 1560 to 1780 | |
| Excess air, % | 10 to 35 | |
| $SO_2$ removal @ Ca/S = 1.5, % | 85 | |
| $SO_2$ removal @ Ca/S = 2.5, % | No $SO_2$ detected | |
| $NO_x$ without staged combustion, ppm | 200 to 250 | |
| $NO_x$ with primary and secondary air, ppm | 90 to 100 | |
| Residual carbon in bed material, % | 0.1 to 0.5 | |
| Residual carbon in fly ash, % | Max. 3, generally 1 | |

[a]Moisture-free.

Source: Reference 1.

TABLE 4. COMPARISON BETWEEN THE CONVENTIONAL FLUIDIZED BED AND THE LURGI CIRCULATING FLUID BED FOR THE COMBUSTION OF COAL

| Criterion | Conventional (bubbling) fluidized bed | Circulating fluidized bed |
|---|---|---|
| Heat exchange surface | Immersed in bed<br>Erosion problems in close packing of tubes | Only tube walls in fluidized bed combustor, with further decoupled heat exchange in an external solids heat exchanger |
| Gas/solids contacting | Restricted to bed heights of 1.6 to 6.6 ft | The whole reactor is filled with dispersed solids - bed height 66 to 100 ft |
| Pressure drop | Similar | Similar |
| Partial load | Down to 70% in one module, complicated controls | Down to 50% per unit and lower, simpler control |
| Load following | Relatively slow | Faster than conventional FBC |
| Bed material | Relatively coarse | Fine |
| Combustion efficiency | Problems with entrained fines are encountered | Virtually complete 99% |
| Coal crushing | Coarse, coal drying may be avoided | Finer particle size, however coarser than pulverized coal combustion. Coal drying may be necessary |
| Excess air ratio | 1.2 - 1.4 | 1.1 |
| Emission characteristics | | |
| a. Ca/S ratio for 90% removal of $SO_2$ with limestone addition | Ca/S = 3 and higher | Ca/S = 1.5 - 2<br>(longer contact time, smaller particles) |
| b. $NO_x$ | 300 - 400 ppm | 100 - 200 ppm |
| c. Particulates | Similar | Similar |
| Coal feed | Complicated, large number of feed points (1 feed point per 10 to 20 $ft^2$). Alternatively overbed feeders have higher carbon losses in fines | Simple, 2 feed points per unit |
| Specific thermal load per unit cross-section | 3.2 to 9.5 x $10^5$ Btu/$ft^2$-hr | 9.5 x $10^5$ to 2.5 x $10^6$ Btu/$ft^2$-hr |
| Temperature uniformity | Freeboard combustion possible due to fines and volatiles | Uniform temperature in reactor and cyclone system due to high solids re-circulation rate. |

Source: Reference 1.

January 1980, the Tennessee Valley Authority awarded a contract for a joint study by Combustion Engineering and Lurgi to perform preliminary design of a 200 $MW_{(e)}$ and an 800 $MW_{(e)}$ utility boiler using the Lurgi CFBC process.[16] This work was completed in December 1980. The 200 $MW_{(e)}$ utility boiler plant is shown in Figure 12. Design parameters are shown in Table 5.

A commercial CFBC unit is being built by Lurgi in Lünen, West Germany at the Vereinigte Aluminumwerke (VAW). This unit will have a capacity of 84 $MW_{(t)}$ and will both produce high pressure steam (convective section) and reheat $2.8 \times 10^6$ lb/hr molten salt heat carrier from 650° to 800°F (fluid bed heater section). On equivalent terms the unit, if designed for steam production only, would produce 220,000 lb/hr of steam. (See Figure 13). The unit will burn high ash coal waste (50 percent by weight, dry basis). The project began in 1980 and is scheduled for commissioning in mid-1982.*

PYROPOWER CORPORATION[18-23]

The Pyropower Corporation, formed in September 1980, is equally owned by General Atomic Company of San Diego, California and Ahlstrom Company of Helsinki, Finland. Fluidized-bed combustion research has been one of the major projects at the Hans Ahlstrom Laboratory--the R&D Department of the Company's Engineering Division in Karhula, Finland--since 1969. Conventional bubbling fluidized-bed systems have been developed for incineration of such wastes as sewage sludge, oily sludge, peat and other materials and liquids, and for heat and steam generation. A total of nine conventional systems have been sold by Ahlstrom for commercial application in Australia, England, Finland, France, Sweden, and Syria.

Limitations with conventional fluidized beds (need for many fuel feed points and limits on the range of fuels to be burned and the fines content to achieve good combustion efficiencies) led Ahlstrom to develop the PYROFLOW™ circulating fluidized-bed system in 1976. This technology has been developed in the company's 2.0 $MW_{(t)}$ pilot plant, which has been in operation since 1977. Two basic system configurations are offered for steam generation as shown in Figure 14. For the low-to-medium pressure steam applications, a convective boiler bank is required since all of the evaporative duty cannot be done in the combustion chamber. A superheater is located at the inlet to the boiler bank while an economizer for heating incoming feedwater is situated at the boiler bank outlet. For the medium-to-high pressure steam applications, all evaporation will be done in the combustion chamber and superheating will be done in the convection zone of the boiler. An economizer is also installed in the convection zone. Depending on the fuel to be used, an airheater may also be included in this second configuration.

The PYROFLOW circulating bed system uses greater air velocities than conventional FBCs and the entrained particles are separated from the hot gases in a cyclone collector and reinjected into the bottom of the combustion

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*Personal Communication between John Milliken, EPA, and Phil Mantin, Lurgi Corp., October 29, 1981.

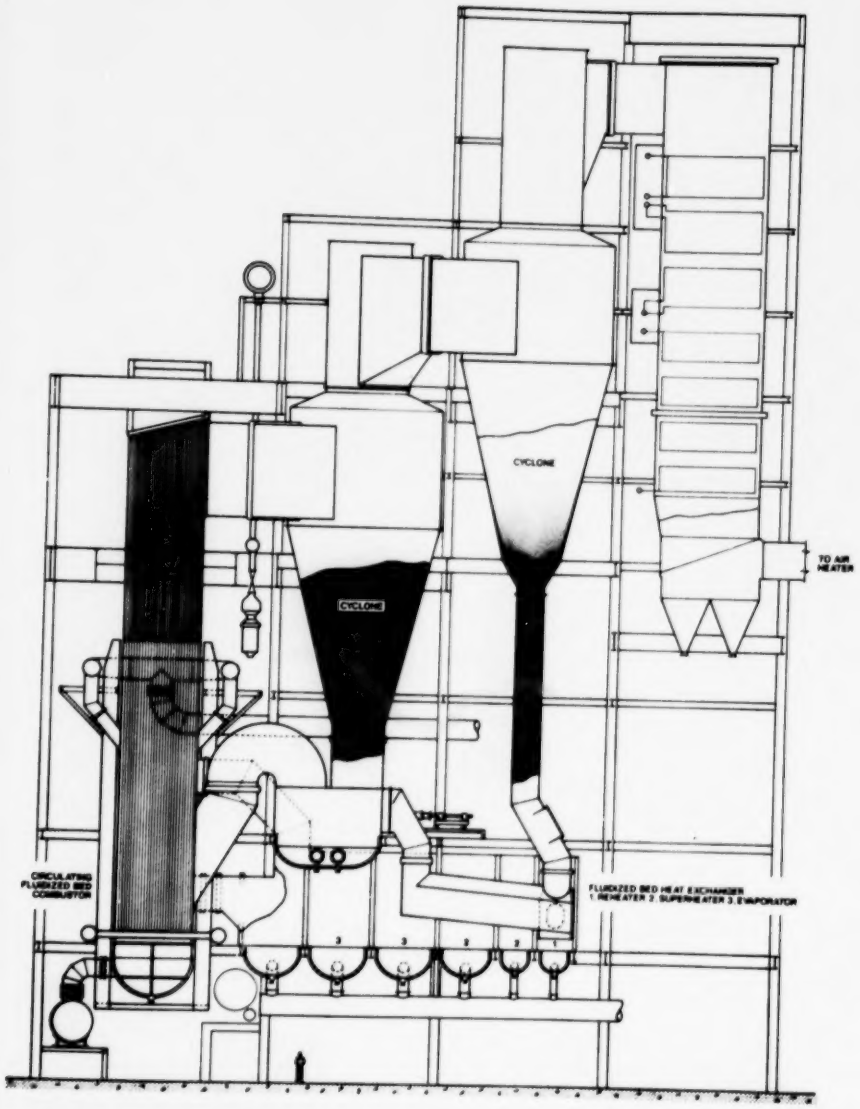


Figure 12. 200 $MW_{(e)}$ CFB utility unit.
Source: Reference 16.

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TABLE 5. DESIGN PARAMETERS FOR 200 MW(e) CFBC CONCEPTUAL DESIGN STUDY[a]

| | |
|---|---|
| **Circulating Fluid Bed Combustor--** | |
| Combustion temperature: | 1560°F |
| Excess air ratio: | 1.2 |
| Fluidizing velocity: | 19 ft/sec |
| Average carbon content of ash: | 1 percent |
| Combustion efficiency: | 99.4 percent |
| Ca/S mole ratio: | 1.5 |
| Sulfur removal efficiency: | 90 percent |
| CFB pressure drop: | 104 in. W.C. |
| Heat transfer coefficient to CFB tube walls: | 30 Btu/ft$^2$-hr-°F |
| Number of coal feed points: | 1 per 50 MW(e) |
| Number of limestone feed points: | 1 per 100 MW(e) |
| Solids entrainment from CFB furnace: | 0.15 lb/ft$^3$ gas |
| Mean coal feed size: | 300-500 μm |
| Mean limestone feed size: | 250-400 μm |
| **Cyclones--** | |
| Axial velocity: | 10.5 ft/sec |
| Recycling cyclones efficiency: | 96 percent |
| Secondary cyclones efficiency: | 85 percent |
| **Fluid Bed Heat Exchanger--** | |
| Fluidizing velocity: | 3 ft/sec |
| Heat transfer coefficient to immersed tube surface: | 70 Btu/ft$^2$-hr-°F |
| FB heat exchanger pressure drop: | 36 in. W.C. |

[a]Source: Reference 16.

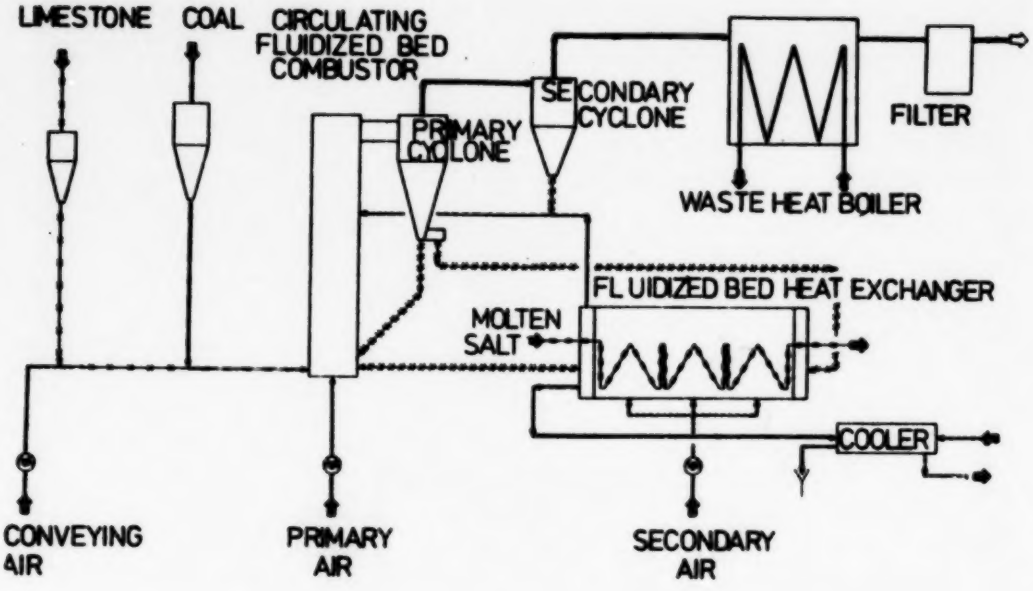



Figure 13. Flow diagram of a Circulating Fluidized-Bed Combustion Plant.

Source: Reference 17.

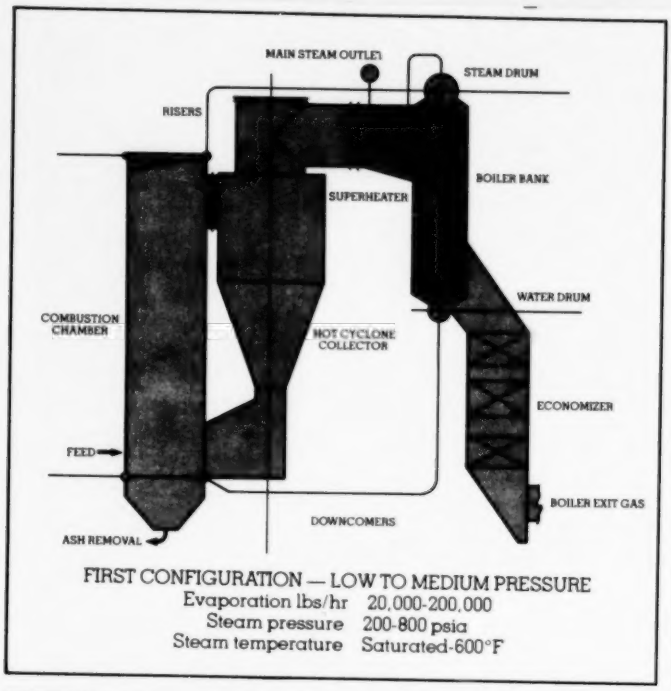



**Figure 14. Commercial system configurations offered by Pyropower Corporation.**

**Source: Reference 21.**

chamber. Turndown ratios of 4:1 can be provided merely by changing flow rates and fuel feed, and 50 percent load changes within 3 minutes have been demonstrated. Fuel is fed into the lower combustion chamber and primary air is introduced through a lower grid. While there is no definite fixed bed depth, the density of the bed does vary throughout the system with the highest density at the level where the fuel is introduced. Secondary air is supplied at various levels to assure gas velocities higher than particle falling velocity. Combustion takes place at about 1550°F, which is considered optimum for sulfur retention in a coal/limestone system. A cyclone collector separates hot gases from the unburned particles and entrained bed material; the particles are returned to the combustion chamber through a non-mechanical seal, and ashes are removed through the bottom. Effluent gases from the cyclone are discharged to the convection section of the boiler. Some of the heat is absorbed by water walls in the combustion chamber, while the remainder is recovered in the convection zone.

Major performance features of the PYROFLOW circulating bed system are as follows:

- It has a high processing capacity (relative to conventional FBC) because of the high gas velocity throughout the system.
- The operating temperature of 1550°F is reasonably constant throughout the process due to the high turbulence and circulation of the solids. This relatively low combustion temperature results in minimal $NO_x$ formation.
- Sulfur present in the fuel is retained in the circulating solids in the form of calcium sulfate and is thus removed in solid form. The use of limestone or dolomite sorbents allows a high sulfur retention rate, and the sorbent requirements are substantially lower than those for conventional FBCs.
- Combustion air is supplied at 1.5 psig rather than higher pressures required by conventional FBCs.
- It has a high combustion efficiency.
- It has a better turndown ratio than conventional FBC systems.
- Erosion of heat transfer surfaces is reduced since the surface is parallel to the gas flow. In conventional FBC systems, the surface is usually perpendicular to the flow.

A list of Pyropower's commercial circulating bed installations since 1976 is provided in Table 6. Since the first circulating bed system was developed at Ahlstrom, 11 additional systems in sizes up to 200,000 lb steam/hr have been sold for commercial operation. One system has accrued 2 years of operation with an availability of over 95 percent. Another system represents the first U.S. installation for Pyropower Corp. and will be used to make steam for an enhanced oil recovery project near Bakersfield, California. A brief discussion of some of these industrial applications is provided in the following paragraphs.

TABLE 6. PYROFLOW™ CIRCULATING FLUIDIZED-BED UNITS IN OPERATION OR UNDER CONSTRUCTION BY PYROPOWER CORP.[a]

| Customer | Year of startup | Fuels | Application | Size |
|---|---|---|---|---|
| 1. Hans Ahlstrom Laboratory<br>Karhula, Finland | 1976 | Varied | Pilot plant | 2 $MW_{(t)}$ |
| 2. Ahlstrom Company<br>Pihlava, Finland | January 1979 | Peat, wood wastes, and supplementary coal | Cogeneration for board mill | 5.67 kg/s - 15 $MW_{(t)}$<br>(45,000 lb/hr steam) |
| 3. Savon Voima Company<br>Suonenjoki, Finland | September 1979 | Peat, wood wastes, and coal | District heating | 7.0 $MW_{(t)}$ |
| 4. Kemira Company<br>Valkeakoski, Finland | 1980 | Zinciferous sludge | Incineration | 0.71 kg/s<br>(5650 lb/hr)<br>(21.5% dry) |
| 5. Ahlstrom Company<br>Kauttua, Finland | March 1981 | Peat, wood wastes, and coal | Cogeneration | 25 kg/s - 65 $MW_{(t)}$<br>(200,000 lb/hr steam) |
| 6. Hyvinkaa Lampovoima Company<br>Hyvinkaa, Finland | Fall 1981 | Coal primary, alternate peat or oil | District heating | 25 $MW_{(t)}$ |
| 7. Skelleftea Kraft Company<br>Skelleftea, Sweden | Fall 1981 | Peat, wood wastes and coal | District heating | 7.0 $MW_{(t)}$ |
| 8. Town of Ruzomberok<br>Ruzomberok, Czechoslovakia | Fall 1981 | Sewage and industrial sludges | Incinerator | 1.11 kg/s<br>(8800 lb/hr)<br>(26% dry) |
| 9. Hylte Bruk Company<br>Hylte Bruk, Sweden | Fall 1982 | Peat primary, coal alternate | Cogeneration | 18.27 kg/s - 50 $MW_{(t)}$<br>(145,000 lb/hr steam) |
| 10. Alko Company<br>Kosken Korva, Finland | 1982 | Peat | Process steam | 7 kg/s - 16 $MW_{(t)}$<br>(56,000 lb/hr steam) |
| 11. Kemira Company<br>Finland | 1983 | Peat, coal, and coal wastes | Cogeneration | 19.5 kg/s - 52 $MW_{(t)}$<br>(155,000 lb/hr steam) |
| 12. Gulf Oil Exploration and Production Co.<br>Bakersfield, California | January 1983 | Coal | Process steam for enhanced oil recovery | 50 x $10^6$ Btu/hr input |

[a]Source: 1-9: Reference 22.
10-11: Personal Communication between John Milliken, EPA, and Eric Oakes, Pyropower Corp., October 15, 1981.
12: Chemical Engineering, April 5, 1982, pp. 39-43.

At the end of 1977, Ahlstrom decided to install its first commercial PYROFLOW system at its own board mill power plant in Pihlava, Finland. Construction of this retrofit installation was completed by the end of December 1978; the commissioning period began in January 1979 and the unit began commercial operation in April 1979. A schematic diagram of this installation is shown in Figure 15. The water-tube-cooled combustion chamber is coupled in parallel to the furnace circuit of the main boiler, delivering a saturated steam/water mixture to the drum. Over half of the heat generated by the PYROFLOW combustion process is in the flue gases, which leave the combustion chamber at 1600°F. The distribution of heat input and steam absorption during the normal 32 $MW_{(t)}$ plant output at 100 percent load is as follows:

| | $MW_{(t)}$ |
|---|---|
| Heat Input | |
| La Mont boiler | 20 |
| PYROFLOW | 17 |
| | 37 |
| Steam Generated | |
| La Mont boiler | 25 |
| PYROFLOW water wall | 7 |
| Total | 32 |

Note: Boiler efficiency = 86 percent.

During the last 2 years there were production restrictions that resulted in periods of low steam demand during which the PYROFLOW unit was shut down, leaving the reduced steam production to the La Mont boiler. This was done because the PYROFLOW is easier to start up. Because of many periods of shutdown and low load operation, it was difficult to assess an availability figure for the CFBC. A review of plant records from April 1979 to December 1980 revealed that over 10,000 hr of on-line operation were accumulated. This indicates an availability of 95 percent. The PYROFLOW system did not cause any forced shutdown throughout 1980, and a thorough inspection at the end of the year revealed that all areas of the furnace and refractory were in good condition with no signs of wear.

The Pihlava size unit (45,000 lb steam/hr) requires only one fuel feed point, which is fed by a screw feeder. A variable-speed hydraulic motor drives this screw feeder, which is sized to feed peat, but will also accommodate bark, wood wastes, and coal. This feed system lends itself to an effective means of automatic load following.

An example of this system's operating parameters during an abnormal load swing is shown in Figure 16. These plots show a load reduction because of a

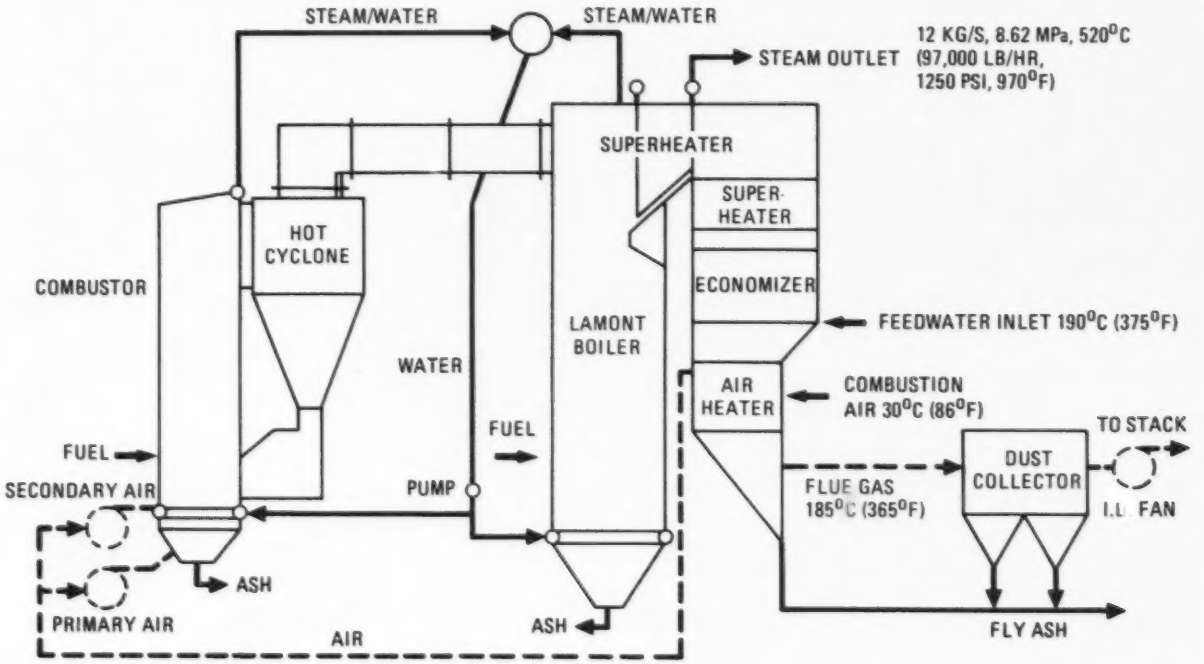



Figure 15. Pyroflow™ combustion chamber retrofitted to La Mont boiler at Pihlava board mill, Finland.

Source: Reference 22.

disturbance in the intermediate steam pressure system of the board mill. At midnight on April 3, 1980, the boiler was operating at 30 ton/hr output with most of this output generated by the PYROFLOW combustion unit. At midnight, the steam output demand decreased from 30 to 20 ton/hr, which was effected by a 50 percent load reduction in the PYROFLOW combustor. The curves in Figure 16 indicate how the main steam pressure remained fairly constant during the load swing and the period of low-load operation. The two low-pressure peaks prior to the load reduction were due to sootblowing. The complete upset and return to full load were handled fully automatically by the PYROFLOW screw feeder governed by the boiler control equipment.

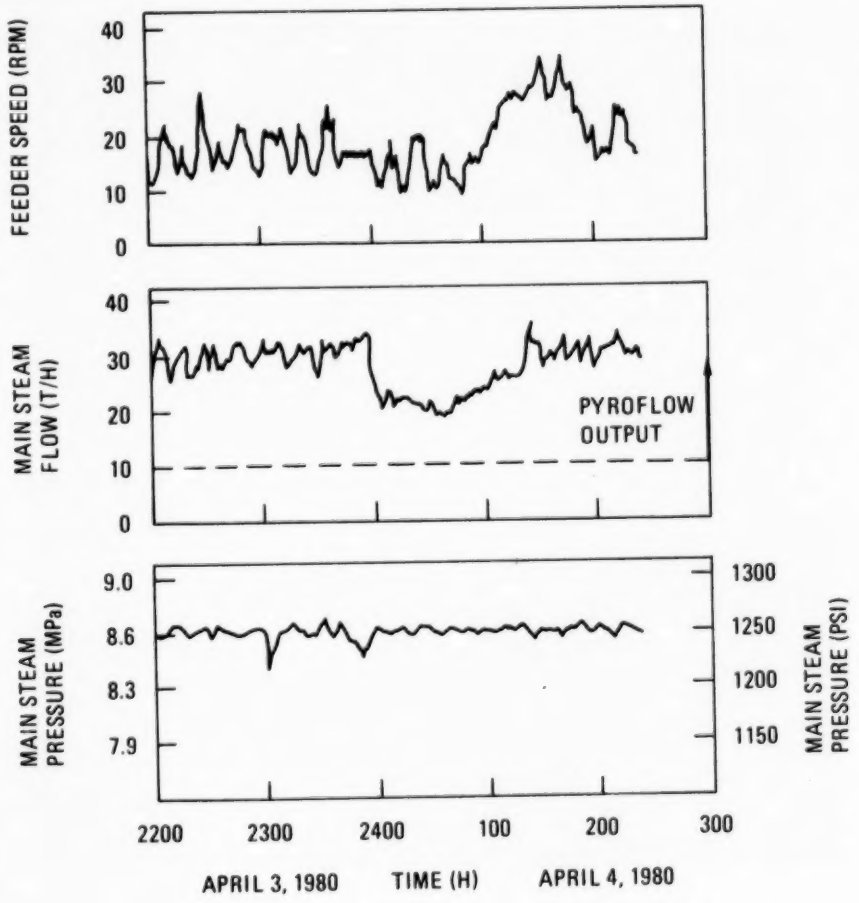



Figure 16. PYROFLOW upset transient response.

Source: Reference 22.

The PYROFLOW unit at the Pihlava plant was installed solely for economic reasons (to reduce the high operating cost associated with firing fuel oil) since standards in effect at the time of installation did not require the use of FBCs for $SO_x$ or $NO_x$ control. The environmental control aspects and the capability to fire several fuels have proven to be supplemental advantages of the Pyropower circulating fluid bed system. Emissions of $NO_x$ when burning peat have been consistently about 250 ppm. The capital costs of this retrofit installation were about $1 million (1978) and during the first year of operation this investment was paid back by the operating cost savings realized by replacing fuel oil with peat, wood waste, and coal. Manpower requirements were the same as when firing oil.

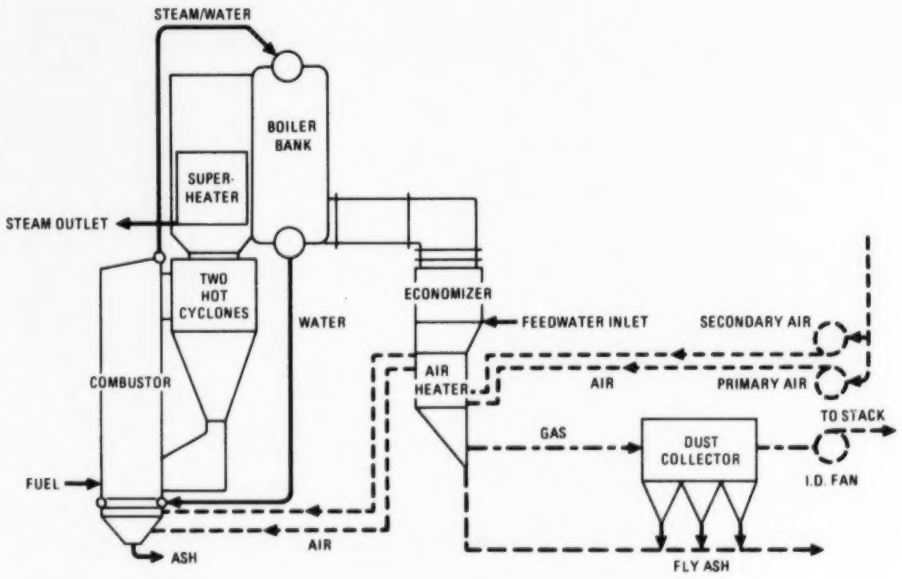
Also during 1979, a 7 $MW_{(t)}$ district heating circulating bed system went into service in the city of Suonenjoki, Finland. This plant is a turnkey installation to provide 248°F water. The design fuels are peat, bark, and wood wastes, but the plant can also burn coal as a supplementary fuel. No other information is available on this facility.

In 1978, Ahlstrom evaluated replacing the existing fuel oil-fired boilers at its pulp and paper mills at Kauttua in Western Finalnd with units capable of burning wood wastes, peat, and coal. Based on the successful operating experience of the 22 ton/hr unit at Pihlava and further testing of various fuels at the Hans Ahlstrom Laboratory, a single 100 ton/hr PYROFLOW boiler was selected for cogeneration at the Kauttua mills. A schematic diagram of the plant configuration and the design specifications are indicated in Figure 17. Plant startup and commissioning began in March 1981. As well as replacing the two existing oil-fired boilers, an additional 14 $MW_{(e)}$ back-pressure turbine-generator set was added to the existing 8-$MW_{(e)}$ back-pressure capacity. Under full-load conditions a total of 22 $MW_{(e)}$ can be generated along with process steam for the pulp and paper mills. It should be noted that this installation is the largest cogeneration steam plant in the world using the circulating bed technique.

Those circulating fluidized-bed combustion systems sold by Pyropower Corp. and operated thus far have demonstrated the following characteristics:

- multifuel capability
- good boiler efficiency
- good load-following capability
- high availability
- ease of operation
- economical installation to replace oil firing

Pyropower Corp. is now offering PYROFLOW systems to the North American market and to support this effort a testing program was initiated in 1979 at




Design Specifications:

| | |
|---|---|
| Steam output | - 25 kg/s (200,000 lb/hr) |
| Steam temperature | - 500°C ±7.8°C (932°F ±18°F) |
| Steam pressure | - 8.4 MPa (1218 psig) |
| Feedwater temperature | - 190°C (374°F) |
| Flue gas temperature | - 160°C (320°F) |
| Design fuel | - Peat, 8 MJ/kg (3440 Btu/lb) |
| Efficiency with design fuel | - 86% |
| Other fuels | - wood wastes and coal |

Figure 17. 100 ton/hr cogeneration plant at Kauttua paper mill, Finland with specified operating conditions.

Source: Reference 22.

the 2.0 $MW_{(t)}$ pilot plant at the Hans Ahlstrom Laboratory in Finland. Testing has been conducted on high sulfur U.S. coals, petroleum coke and U.S. lignite. The Electric Power Research Institute (EPRI) and the Tennessee Valley Authority (TVA) are participating in this program and have supplied two types of Eastern, high sulfur bituminous coal (Ohio No. 6 and Kentucky No. 9) and a North Dakota lignite (Buelah) for testing. Operating conditions and initial test results while burning the Ohio No. 6 coal are shown in Table 7, while overall typical results from further testing of these fuels are shown in Table 8.

OTHER EFFORTS

Several other groups and organizations have been involved in research related to circulating fluidized-bed combustion technology.

Combustion Engineering (CE), Conoco, and Stone and Webster are involved in a joint venture concerning development of a Solids Circulation Boiler for industrial application (burning of high sulfur coal).* This concept is basically opposite to that employed in other CFBC configurations in that combustion of coal takes place in the dense or bubbling bed while heat exchange occurs in the dilute or entrained bed. Highlights of the concept are as follows:[24]

- Combustion is carried out in a highly agitated circulating fluid bed of inert material. Fuel and limestone are introduced to the combustion zone where they are rapidly distributed throughout the bed by the swirling action of the solids.

- Steam is generated by passing hot solids from the combustion zone through a water-walled channel in first an upward and then a downward flow, using secondary air as the solids transfer medium. Evaporation to steam is maintained at the desired rate by controlling the quantity of solids circulating through the channel.

- Cooled solids from the downflow channel return to the combustion zone in a cascade over the bed surface with the accompanying secondary air. The cascade reduces entrainment from the bed, breaks up bubbles of gas formed in the bed, assists in the solids circulating action within the bed, and maintains the combustion zone in heat balance and thereby constant temperature.

A cold test unit was constructed in April 1980 at the Conoco Coal Development Company facility in Library, Pennsylvania. A hot test unit commenced operation in February 1981 at Combustion Engineering's Kreisinger Development Laboratory in Windsor, Connecticut.

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*Personal communication between Doug Roeck, GCA and Dr. Melvin Pell, Conoco Coal Development Company, Library, Pa., August 10, 1981.

TABLE 7. INITIAL RESULTS FROM TESTS ON OHIO NO. 6 COAL

| | |
|---|---|
| **Operating Conditions** | |
| Combustion temperature | 1600°F |
| Superficial gas velocity | ∿12 ft/sec |
| Ca/S ratio | 2.25 |
| Excess air | 15% |
| Secondary air | 20% of total air |
| Coal feed rate | 440 lb/hr |
| Limestone feed rate | 150 lb/hr |
| **Test Results** | |
| $SO_2$ retention | 90% |
| Ca/S ratio: | 1.4 to 2.25 |
| $NO_x$ emissions: | 170 ppm |
| CO emissions: | 200 ppm |
| Combustion efficiency:[a] | 97% |

[a]Without recycling fines from a secondary cyclone. Combustion temperature was 1600°F over a 6-1/2 hour steady-state period, and all emissions were measured at 15 percent excess air.

Source: Reference 18.

TABLE 8. PRELIMINARY RESULTS OF FUEL TESTS FOR NORTH AMERICAN MARKET[a]

| Parameters | Fuel | | | |
|---|---|---|---|---|
| | Subbituminous coal | 80 percent ash fuel | Ohio No. 6 coal | Petroleum coke |
| • Sulfur content, % by wt. in dry matter | 0.9 | 2.5 | 5.1 | 3.5 |
| • Nitrogen content, % by wt. in dry matter | 1.1 | 0.3 | 1.5 | 1.8 |
| • Ca/S molar ratio (average) | 2.3 | 2.3 | 1.8 | 2.4 |
| • $SO_2$ retention, % | 84 | 98 | 90 | 90 |
| • $NO_x$, ppm (v) | 170 | 200 | 280 | 100 |
| • Combustion Efficiency, % | 98.0 | 98.5 | 98.5 | 97.0 |

[a]All tests run at 20 to 30 percent excess air.

Source: Reference 22.

The Tennessee Valley Authority (TVA) and the Electric Power Research Institute (EPRI) have examined advanced coal combustion technologies for use in the utility industry and in order to develop performance data for the CFBC process, TVA contracted Lurgi Chemie to perform a number of test burns with various U.S. coals and limestones. EPRI has participated in planning the tests and supplying various fuels.

The coal combustion tests were conducted in one of Lurgi's CFB pilot plants in Frankfort, West Germany. A simplified flow scheme of this pilot facility is illustrated in Figure 18. Only a brief summary of the results of this test program are presented herein; the reader is referred to the original reference for more detailed information.[25]

The pilot CFBC has an internal diameter of 14-inches, a height of 13 feet, and is refractory-lined. Effluent gas from the combustor leaves the recycling cyclone and flows through an empty venturi stage and two further cyclones before being discharged to a baghouse for final dust collection.

Testing was done with four U.S. coals (Ohio No. 6, Kentucky No. 9, Freeman, and Beulah-Lignite) and two U.S. limestones (Lowellville and Vulcan). In addition, a German coal (Ruhr) was burned to show reproducibility of results previously obtained and a German limestone (Schaefer) was used for comparative purposes. The following combinations of coals and limestones were tested over a total of 35 test runs of different parameter combinations:

1. Kentucky No. 9 coal and Vulcan limestone

   - These are the design coal and limestone selected by TVA for the 200 and 800-MW AFBC and CFBC conceptual design studies being performed by Combustion Engineering and Lurgi.

2. Ohio No. 6 coal and Lowellville limestone

   - This combination has been previously tested at B&W in Alliance, Ohio under EPRI sponsorship.

3. Freeman coal and Lowellville limestone

   - This combination has been previously tested by Combustion Engineering.

4. Beulah lignite

   - Whereas unfavorable slagging characteristics have been observed with this coal in previous AFBC tests conducted by DOE (at the Grand Forks, ND and Morgantown, WV Energy Technology Centers and at Combustion Power Company in Menlo Park, CA), the performance of this coal in the CFBC was of interest for comparison.

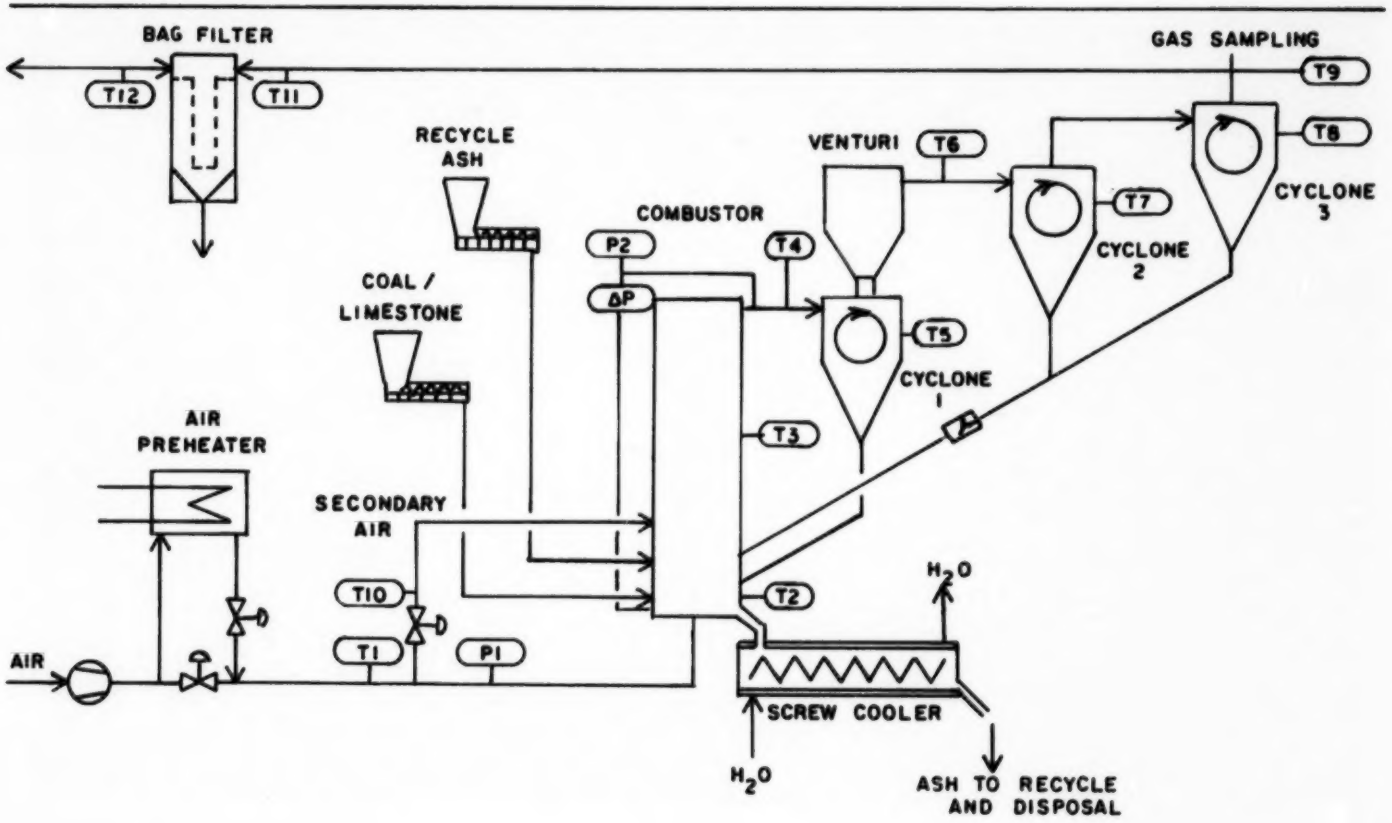


Figure 18. Circulating Fluid Bed Pilot Facility at Lurgi, Frankfort, West Germany.
Source: Reference 25.

5. Ruhr coal and Schaefer limestone

   - These materials were tested to show reproducibility of earlier results.

The coal combustion tests were conducted at temperatures of 1450° to 1750°F and at excess air ratios of between 1.1 and 1.3. Carbon combustion efficiency for all tests was found to be generally above 99.5 percent. Other general conclusions of this overall program were as follows:

- the Ca/S molar ratio required for 90 percent $SO_2$ removal was found to be as low as 1.0 for the circulating bed. Past work with conventional FBC units has indicated that a Ca/S ratio of 2.5 or more would be required for the same level of $SO_2$ reduction. (Recent work for TVA on a small scale AFBC unit indicates that a Ca/S ratio of possibly as low as 1.25 is attainable with recirculation of cyclone and baghouse catch, but the advantage still appears to be in favor of the CFBC.)

- In conventional bubbling beds, 90 to 94 percent carbon utilization can be attained without recycle of fly ash while with high recycle, 99 percent utilization has been approached. The results of the TVA test program showed that generally better than 99.5 percent carbon utilization was achievable with the CFBC.

- In general, $NO_x$ emissions were the same or slightly lower with the CFBC compared to conventional bubbling beds. It was felt, however, that better results could be attained for the CFBC in larger scale equipment.

As a result of the rather encouraging test results from this program, TVA has initiated construction of a 20-$MW_{(e)}$ pilot plant at its Shawnee generating facility. This unit will be a hybrid CFB-AFBC, with a design recirculation rate of five times the coal feed rate.

Several research efforts have also been undertaken in Sweden involving the CFBC process. At the Lund Institute of Technology, a reactor concept has been developed that operates with circulating fluidized-beds and segregated gas phases.[26] The reactor has been demonstrated to work in the gasification of black shale, utilizing the char as a heat carrier. The reactor principle can also be applied to physical operations such as activated carbon adsorption. Other work is being done at Studsvik Energiteknik AB in Nykoping, Sweden and relates to a 250 kW fast fluidized-bed experimental model designed for cold flow and combustion experiments.[27,28] Following experience with the 250 kW experimental unit, work on circulating fluidized bed combustors at Studsvik has aimed at developing a 2.5 MW prototype module. This unit is intended to be as nearly full scale as possible in order to minimize the problems normally encountered on scaling up. Thus the height and depth of the

unit (see Figure 19) are in accordance with the design parameters for a 25 MW bed and the heat generated is transferred to a hot water boiler operating at a pressure of 16 bar. Scale up is accordingly accomplished by assembling the requisite number of modules. In order to minimize the effect of changes in the ratio of surface area/volume with change of size the two side walls of the 2.5 MW prototype are lined with insulating refractory. The rate of flow of the circulating bed material is governed by non-mechanical valves. The entire boiler is constructed from water tubes welded together to form membrane walls. The construction is similar to that used in the manufacture of conventional oil-fired steam generating plants. As a result there are no structural components that are subjected to high temperatures and it is accordingly possible to avoid the use of refractory materials for heat shielding (with the exception of those used in the prototype to reduce heat transfer). The particle recirculation and separation units are an integral part of the main furnace body. At Gotaverken in Göteborg, Sweden, construction has been nearly completed on an 8 $MW_{(t)}$ demonstration CFBC that will provide steam for the company's shipyard.* Coal firing is expected to begin early in 1982 with peat and wood to be used as alternate fuels. A single screw feeder will be used for each fuel type. The fluidizing velocity for this system will be 26 to 33 ft/sec. Particulate control will be achieved with a baghouse and gaseous emissions will be continually monitored.

The Westinghouse R&D Center in Pittsburgh, Pennsylvania has also investigated circulating bed boiler concepts.[29] A deep recirculating fluidized-bed combustion boiler (Figure 20) was conceived by Westinghouse as an alternative to conventional atmospheric and pressurized fluid bed units. Westinghouse developed a design for this concept operated at elevated pressure. Westinghouse has estimated that pressure losses for atmospheric pressure circulating-bed boiler systems would be about 2.7 in. W.C. per foot of bed height and that overall pressure loss including combustor, air preheater, particulate control, convection heat transfer, ducting, etc., would range from 50 to 80 in. W.C.

## ECONOMICS

The costs of circulating fluidized-bed combustion systems are not well defined at this point in time due to a general lack of commercialization of the process in the U.S. However, a limited amount of cost data comparing circulating FBC to conventional FBC are available.[30-32] These data indicate that CFBC capital investment costs are similar to those for conventional FBC systems, and that operating costs for CFBC may be slightly less. The following paragraphs describe these cost studies which are very much preliminary and therefore should be considered in that light.

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*Personal communication between Bob Hall, GCA, and Dr. Anders Kullendorff, Gotaverken, November 11, 1981.

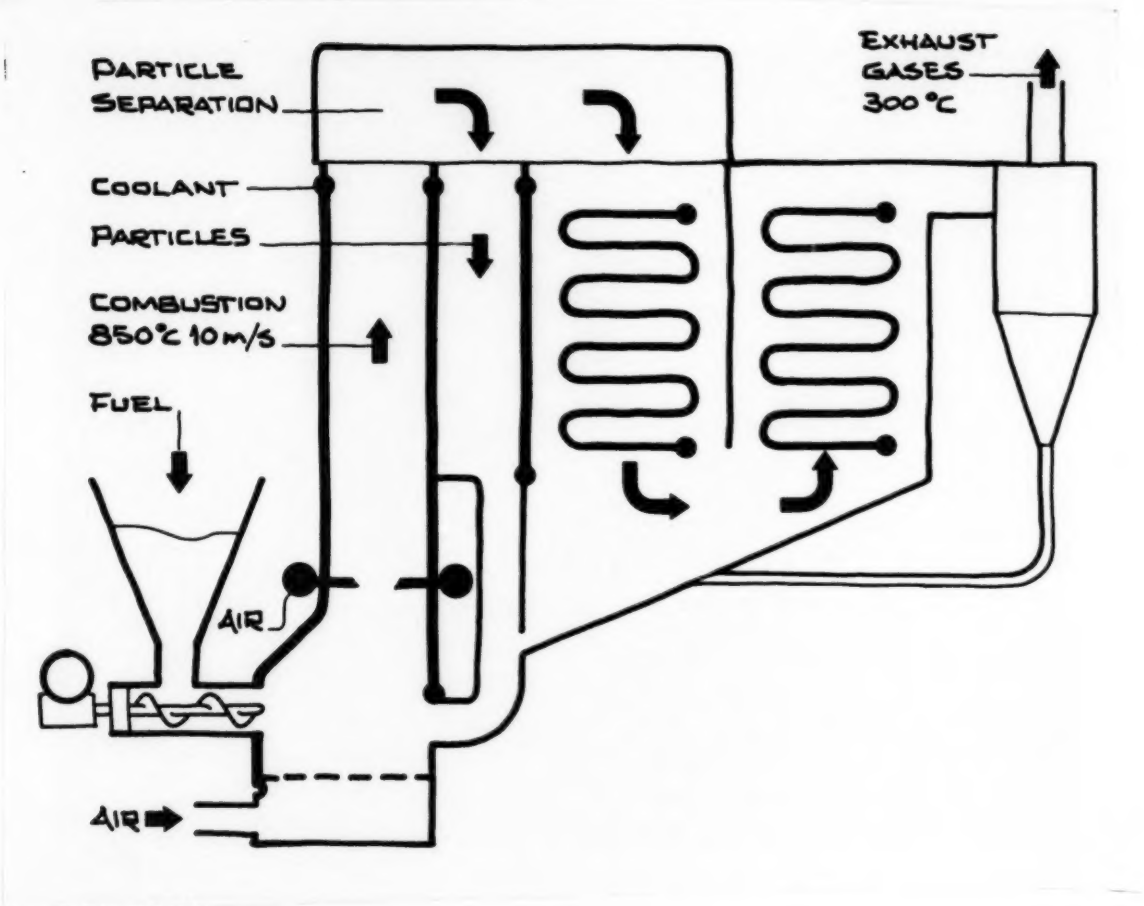


Figure 19. Schematic Diagram of 2.5 MW CFBC Prototype Module Being Developed at Studsvik, Sweden.

Source: Personal communication between John Milliken, EPA and Allan Brown, Studsvik.

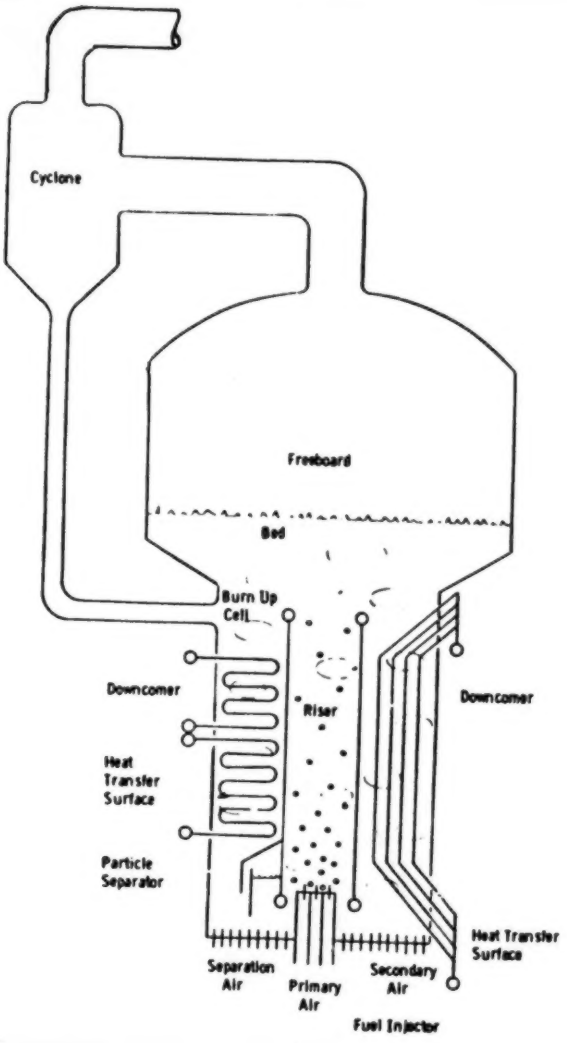


Figure 20. Deep recirculating fluidized-bed boiler.
Source: Reference 29.

Pullman Kellog Company has performed conceptual design studies for the Electric Power Research Institute comparing a circulating bed boiler with a conventional pulverized coal boiler.[30,31] Relative to costs, conclusions of this study were:

1. A circulating bed boiler should not exceed a conventional atmospheric fluidized-bed combustor in capital cost, and will probably be less, due to reduced combustor size. The cost advantage of a pressurized circulating bed boiler is questionable.

2. The overall efficiency of an electric utility power plant should be increased by at least 1 percent over a pulverized coal boiler--using an atmospheric circulating bed boiler, and by at least 3 percent--using a pressurized circulating bed boiler.

3. Actual capital costs for CFBCs could not be determined due to a lack of data.

The overall performance of the atmospheric CFBC plant compared to one using a pulverized coal boiler is summarized in Table 9. Both systems were designed to meet the following standards:

Particulate matter - 0.05 lb/$10^6$ Btu

$SO_2$ - 90% removal

$NO_x$ - 0.6 lb/$10^6$ Btu

The major difference between the two plants is in auxiliary power consumption, primarily due to a higher system pressure loss in the CFBC. According to the study, it would be possible to boost the CFBC net plant efficiency from 34.9 percent to 38.8 percent with a high efficiency supercritical steam cycle.

Only one other study was found that provided a direct comparison between the CFBC and conventional FBCs.[32] In this program, performed under a Department of Energy contract, a cost comparison study was performed on three 100,000 lb steam/hr boilers of the following designs: the Battelle MS-FBC system, a conventional FBC system, and a conventional spreader stoker boiler equipped with a double-alkali flue gas desulfurization system. The design conditions for this analysis were as follows:

| | |
|---|---|
| Steam conditions: | 100,000 lb/hr @ 150 psi |
| Coal analysis: | Illinois No. 6<br>3.5% sulfur<br>10.0% ash<br>10,500 Btu/lb |
| Boiler utilization: | 65% (5,694 hr/yr) |

TABLE 9. CIRCULATING BED VERSUS PULVERIZED COAL BOILER PERFORMANCE

| | Circulating bed combustor plant | Pulverized coal plant |
|---|---|---|
| Heat input from coal, Btu/hr | $5.18 \times 10^9$ | $5.32 \times 10^9$ |
| Gross plant output, MW | 580.06 | 570.17 |
| Auxiliary power consumption, MW | | |
| Steam plant | 8.49 | 8.49 |
| Fans | 34.20 | 15.74 |
| Scrubber | - | 11.49 |
| Others | 7.65 | 8.62 |
| Total | 50.34 (33 $kW/MW_{(t)}$) | 44.25 (28 $kW/MW_{(t)}$) |
| Net plant output, MW | 529.72 | 525.92 |
| Net plant efficiency, % | 34.90 | 33.74 |

Source: Reference 31.

| | |
|---|---|
| Plant location: | Chicago, Illinois |
| Emission standards: | Particulate matter - 0.1 lb/$10^6$ Btu<br>$SO_2$ - 1.8 lb/$10^6$ Btu<br>$NO_x$ - none |

The results of this study are shown in Table 10. Although a slight advantage is shown for the MS-FBC system, given the accuracy of the cost estimates (±25 percent), the costs can be judged to be virtually identical. A detailed breakdown of the operating costs was available only for the MS-FBC and this is shown in Table 11. For comparison with the auxiliary power consumption figures provided earlier in Table 9, electrical consumption for the MS-FBC was determined to be roughly equivalent to 21 $kW/MW_{(t)}$ with particulate control and 16 $kW/MW_{(t)}$ without.

TABLE 10. RESULTS OF COST COMPARISON STUDY FOR CONVENTIONAL FBC, MS-FBC, AND CONVENTIONAL STOKER-FIRED BOILERS[a]

| Component systems | Type of boiler system | | | | | |
|---|---|---|---|---|---|---|
| | Conventional fluidized-bed (FBC) | | Multi-solids fluidized-bed (MS-FBC) | | Stoker-fired | |
| | Capital cost | Oper. cost/yr | Capital cost | Oper. cost/yr | Capital cost | Oper. cost/yr |
| Coal Receiving | 1060 | 39 | 1060 | 39 | 1060 | 39 |
| Raw coal storage | 1170 | 40 | 1170 | 40 | 1170 | 40 |
| Coal preparation | 630 | 36 | - | - | 630 | 36 |
| Prepared coal storage | 400 | 9 | 350 | 9 | 400 | 9 |
| Limestone storage and receiving | 490 | 137 | 550 | 151 | - | - |
| Boiler | 4100 | 1528 | 4080 | 1598 | 3600 | 1439 |
| Flue gas cleanup | 500 | 79 | 500 | 79 | 1560 | 303 |
| Ash handling and storage | 230 | 86 | 230 | 86 | 190 | 74 |
| Totals | 8580 | 1954 | 7940 | 2002 | 8610 | 1940 |
| Total steam cost[b] ($ per 1000 lb) | 7.35 | | 7.20 | | 7.37 | |

[a]1979 dollars x $10^{-3}$ (±25 percent).

[b]Includes total operating costs plus capital charges.

Source: Reference 32.

TABLE 11. COMPONENT OPERATING COSTS ($/yr) FOR 100,000 lb/hr MS-FBC[a]

| Items | Component systems | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Coal receiving | Raw coal storage | Coal prep. | Coal storage | Limestone storage and receiving | Boiler | Flue gas cleanup | Ash storage | Totals |
| Raw Materials and Fuel | | | | | | | | | |
| Coal | | | | | | 1,032,640 | | | 1,032,640 |
| Oil | | | | | | 3,000 | | | 3,000 |
| Limestone | | | | | 128,675 | | | | 128,675 |
| Pebbles | | | | | | 21,300 | | | 21,300 |
| Total | | | | | 128,675 | 1,056,940 | | | 1,185,615 |
| All Other | | | | | | | | | |
| Labor | 25,170 | 25,165 | - | 3,430 | 14,875 | 319,095 | 10,295 | 13,730 | 411,760 |
| Electricity | 255 | 1,105 | - | 1,575 | 2,820 | 121,625 | 46,920 | 265 | 174,565 |
| Water | - | - | - | - | - | 20,400 | - | - | 20,400 |
| R&M | 10,000 | 10,200 | - | 2,810 | 2,500 | 31,220 | 14,700 | 4,360 | 75,790 |
| Ash disposal | - | - | - | - | - | - | - | 59,560 | 59,560 |
| General overhead | 3,540 | 3,645 | - | 780 | 2,020 | 49,235 | 7,190 | 7,790 | 74,200 |
| Total | 38,965 | 40,115 | - | 8,595 | 22,215 | 541,575 | 79,105 | 85,705 | 816,275 |
| Grand Totals | 38,965 | 40,115 | - | 8,595 | 150,890 | 1,598,515 | 79,105 | 85,705 | 2,001,890 |

[a]Unit costs as follows:
- operating labor - $11/hr
- coal - $31/ton
- oil - $12.58/bbl
- limestone - $12/ton
- pebble lime - $42/ton
- pebbles - $20/ton
- soda ash - $85/ton
- electricity - $0.04/kW-hr
- water - $0.30/1000 gal
- ash disposal - $5/ton

Source: Reference 32.

## SECTION 3

## SUMMARY AND CONCLUSIONS

This report has presented an update on the technical status of circulating fluidized-bed combustion. Battelle Development Corp. (Columbus, Ohio), Lurgi Corp. (River Edge, N.J.), and Pyropower Corp. (San Diego, Calif.) are undertaking the major efforts in commercializing this process in the United States.

Battelle has conducted pilot plant tests for several years and now has a license agreement with Struthers Thermo-Flood Corp. for selling commercial systems. A $5 \times 10^6$ Btu/hr pilot plant unit is now being installed at the Struthers facility in Winfield, Kansas for enhanced oil recovery and process heater evaluations. A $50 \times 10^6$ Btu/hr plant has been constructed and is undergoing startup at a Conoco tar sands reservoir in Uvalde, Texas. This unit will provide injection steam for enhanced oil recovery operations. Both of these units are expected to be operational in late 1981/early 1982.

Lurgi Corp. is in the process of commercializing CFBC technology in the U.S. although at present there are no units installed. Lurgi's CFBC technology is similar to the Lurgi-designed aluminum trihydrate calcining process of which there are 24 units installed or under construction worldwide.

Pyropower Corp. is now offering commercial CFBC systems in the U.S. based upon the European experience of Ahlstrom Co., Pyropower's parent company. Ahlstrom has sold 10 commercial systems in Finland, Sweden, and Czechoslovakia and one in the U.S. Of the 11 commercial plants, six are currently operational and five are under construction. These units will utilize such fuels as peat, wood waste, coal, and various sludges.

Costs associated with the CFBC process are very preliminary at this point in time. Those studies that have been done indicate that capital investment costs are roughly equivalent to both conventional FBC systems and other conventional coal boilers. Operating costs for the CFBC are considered to be less than other systems although a lack of commercial installations indicates that further cost data would be required before firm conclusions can be drawn.

Much has been reported on the perceived benefits and advantages of the circulating fluid bed; high combustion efficiency, high sulfur retention at low Ca/S mole ratios, adaptability to staged combustion for $NO_x$ control,

good turndown and load following capabilities, reduced heat exchanger fouling due to location away from the combustion zone, and capability to fire a wide range of fuels. In addition, one study has shown that the overall efficiency of an electric utility power plant could be increased by at least 1 percent over a pulverized coal boiler equipped with an $SO_2$ scrubber--using an atmospheric circulating bed boiler. At the same time the circulating fluid bed concept contains some technical and economic uncertainties which must be resolved. For example, those CFBC system designs which employ separate bed boilers will probably operate at a higher pressure drop than conventional systems and may require additional equipment such as hot cyclones. Other potential problems that are specific to the CFBC process are erosion, because of the high flow velocities, and the separation of bed material from effluent gas, which is made more difficult than normal because of the high particle loadings encountered. Additionally, the CFBC would have to demonstrate the ability to operate under load cycling conditions typical of electric utility generating plants.

The future development of the process will probably continue at a more accelerated rate given the current cost of energy and the desire of plant operators to burn solid fuels--especially those of low quality. Should the results of TVA's conceptual design program--which includes the circulating fluid bed--indicate a clear advantage for the CFBC, then EPRI may promote the construction of a 20 $MW_{(e)}$ pilot plant in the U.S. In the meantime, TVA has initiated construction of a hybrid CFB-AFBC at its Shawnee facility.

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